THE GREEN CRAB INVASION:

A GLOBAL PERSPECTIVE,

WITH LESSONS FROM WASHINGTON STATE

by

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For Maria Eloise: may you grow up learning and loving trails and shores

ABSTRACT

The Green Crab Invasion: A Global Perspective,
With Lessons from Washington State

Debora R. Holmes

The European green crab, *Carcinus maenas*, has arrived on the shores of Washington State. This recently-introduced exotic species has the potential for great destruction. Green crabs can disperse over large areas and have serious adverse effects on fisheries and aquaculture; their impacts include the possibility of altering the biodiversity of ecosystems. When the green crab was first discovered in Washington State in 1998, the state provided funds to immediately begin monitoring and control efforts in both the Puget Sound region and along Washington's coast. However, there has been debate over whether or not to continue funding for these programs.

The European green crab has affected marine and estuarine ecosystems, aquaculture, and fisheries worldwide. It first reached the United States in 1817, when it was accidentally introduced to the east coast. The green crab spread to the U.S. west coast around 1989 or 1990, most likely as larvae in ballast water from ships. It is speculated that during the El Niño winter of 1997-1998, ocean currents transported green crab larvae north to Washington State, where the first crabs were found in the summer of 1998. Green crabs have now been found in Washington's two major coastal bays, Willapa Bay and Grays Harbor, and there is fear that they may spread to the Puget Sound region.

Field observations and laboratory experiments have shown that the European green crab both consumes and competes with a vast array of organisms, including clams, oysters, mussels, snails, and other crabs. On an economic level, a widespread green crab invasion could severely injure Washington State's oyster, clam, mussel, and Dungeness crab industries, among others. The biodiversity of local ecosystems could also be affected, with impacts on sensitive species of concern. Upon examination, I have found ten such sensitive species that will become increasingly vulnerable with each new influx of green crabs.

Means of addressing the green crab problem are varied, and include prevention measures, early detection (monitoring), trapping, keeping crabs out of specific areas, pesticides, bounty programs, fisheries, volunteer programs, public education, biological control, genetic alteration, and government incentives. It can be expected that future recruitment of green crabs will occur, but the scope and timing of such recruitment events are difficult to predict. Currently, Washington State's focus is on trapping existing populations of green crabs,

preventing more green crabs from entering state marine ecosystems, and detecting new populations as quickly as possible.

The State of Washington is to be commended for its far-sighted handling of this problem, and may serve as a model for other regions in their handling of invasive marine species. If detection and control does not continue to be implemented, the result will be an exotic species invasion that could not only alter Washington State's marine and estuarine environments, but also cause annual economic losses of up to $24 million dollars.

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This is the last piece of my thesis I write, and I've been looking forward to it.
TO:

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INTRODUCTION

The European green crab, *Carcinus maenas* (L. 1758) is a recent arrival to the shores of Washington State. Its potential for destruction is immense. An invasive species such as the green crab can disperse over large areas, negatively influencing many other species and affecting aquaculture, fisheries, and even recreational fishing. At times the biodiversity of a region may be critically altered by such species. Often, the invaders displace indigenous species, some of which have a tenuous foothold to begin with due to other factors such as pollution (Richter et al. 1997). If and when a large-scale invasion of green crabs occurs in the State of Washington, the disruption they cause may lead to alterations of entire ecosystems, and damage may be far-reaching.

When the European green crab was first discovered in Washington State in 1998, the state provided funds to immediately begin monitoring and control efforts in both the Puget Sound region and on Washington's coast. However, in spite of the fact that small numbers of green crabs have been found in Washington's two largest bays—or perhaps *because* of the fact that these numbers are small—there has been debate over whether or not to continue funding for green crab detection and control. It is my opinion that if prevention, detection, and control strategies do not continue to be implemented here, the result may be an alien species invasion that could greatly alter our marine and estuarine environments. This is not only an important issue for commercial aquaculture, but for biodiversity in general, with possible severe implications for endangered, threatened, and other sensitive species as well.

This thesis addresses the problems that green crabs can cause, both in the State of Washington and around the world, and looks at different methods of prevention, monitoring, and control. It also provides an analysis of Washington State's handling of the green crab invasion to date, including recommendations for the future, based upon these findings.

NON-NATIVE SPECIES AND THEIR IMPACTS IN THE U.S.

Why do so many plant and animal species populations reach critically low levels and end up on endangered, threatened, and other lists of concern? E. O. Wilson has been one of the first scientists to provide a comprehensive view. Writing on the vast numbers of plant and animal species that have become endangered, Wilson (1992) states that the spread of alien species is second only to habitat destruction as a cause. In an overall analysis in which they sought to determine what most affects imperiled species in the United States, Wilcove et al. (1998) also report that "...competition with or predation by alien species..." was second only to habitat destruction as a threat. In their study of 2,490 U.S. imperiled species, they found that this competition with (or predation by) alien species had affected 49% of all species they studied. This percentage covers a variety of plants, mammals, birds, reptiles, amphibians, fishes, mussels, crayfish, beetles, butterflies, and various other invertebrates. Yet another tally indicates that on the U.S. Department of the Interior's endangered or threatened species lists, 40% of those species listed are at risk primarily because of threats by non-indigenous species (Pimentel 1999).

With regard to aquatic species nationwide, Richter et al. (1997) found the three leading threats to be agricultural non-point pollution, alien species, and altered hydrologic regimes. In addition, they found that in the western part of the United States, the dominant threat to aquatic species is that posed by alien species.

They attribute this in part to the ecological sensitivities of eastern versus western species (Richter et al. 1997). In one comprehensive study of the U.S. west coast, Cohen and Carlton (1995) add that introductions of alien marine species have been increasing in the San Francisco estuary in recent years, a scenario not at all uncommon in western bays and estuaries.

The economic costs of non-native species invasions in the United States are also staggering. Non-native species may invade everything from gardens to agricultural fields, as well as natural areas such as wetlands, forests, grasslands, and marine/estuarine environments. Economic losses from such invasions and their subsequent effects are normally estimated to be at least several billion dollars per year (Environmental Inquiry 2001). In one study, Pimentel et al. (2000) estimated that the invasion of exotic weeds and plant pests alone costs the United States $80 billion every year. Total annual losses caused by invasive exotic species in the U.S. are estimated to be $137 billion (Pimentel et al. 2000).

Thus, agreement is widespread that exotic species introductions are increasing, and that these invasions significantly endanger indigenous species and cost the United States an astronomical amount in terms of economic losses. And what is to be done about the issue of invasive species? Perhaps the examination of one specific species' invasion, along with a discussion of past and present attempts to confront it, can yield some clues and possibly serve as a model for future attempts to control invasive species or to prevent their introductions altogether.

CARCINUS MAENAS, THE GREEN CRAB

The invasive species of which I speak—a recent, accidental introduction to the United States' west coast—is the European green crab, *Carcinus maenas*. Fishermen in the San Francisco Bay area, the site of the green crab's first west coast establishment, reported finding green crabs in their traps as early as 1989 or 1990 (Cohen and Carlton 1995). In a few short years, the numbers of green crabs in the area had reached epidemic proportions. In the San Francisco estuary today, it is common for green crabs to be caught in shrimp nets and in bait fish traps, where sometimes hundreds of crabs fill each trap (Cohen and Carlton 1995).

Green crabs are found in salinities of 4-52 ppt (parts per thousand), temperatures down to freezing, and in virtually all types of protected and semi-protected marine and estuarine habitats, including mud, sand, rock, cordgrass marshes, and eelgrass beds. To make matters worse, green crabs are quite prolific, with females spawning up to 185,000 eggs at a time under favorable conditions (Cohen and Carlton 1995). Since these crabs have such wide environmental tolerances, it is estimated that their range could eventually stretch from Baja California to Alaska (Carlton and Cohen 1995; Cohen et al. 1995).

History of the green crab

The green crab, a common shore crab in Europe, is native to the shores of the eastern Atlantic, the North Sea and eastern Baltic Sea, and may be found from its native range of Norway and the British Isles all the way south to Mauritania, northern Africa (Behrens Yamada, unpublished manuscript; Washington Department of Fish and Wildlife 2001a). European green crabs arrived as an invasive species in Australia around 1900, most likely as stowaways in beach rocks used as semi-dry ballast in English ships (Thresher 1997). Green crabs made their first appearance in South Africa in 1983 (Le Roux et al. 1990) and established a large population there, as they have also done in Japan (1984) and South America. *Carcinus maenas* has even been found in Thailand, but its attempted invasion there uncharacteristically failed (Thresher 1997).

Green crabs were first found on the United States' Atlantic coast in 1817 (Say 1817). *Carcinus maenas* did not, however, manage to reach the Pacific coast until somewhere around 1989 (the exact date is unclear). At that time, the most likely mode of transport was as larvae in ballast water, although adults may have been present in algae used to pack New England bait worms or lobsters. The crabs may also have been transported in the seawater pipe systems of ships or released as discarded research material (Carlton and Cohen 1995; Cohen et al. 1995).

As stated earlier, the green crab's first establishment on the U.S. west coast was in the San Francisco Bay and delta area, where crabs were first reported around 1989. However, it is believed by some that these crabs were present in the area much earlier, and had been building up numbers in warm lagoons and sloughs before dispersing into the rest of the bay (Cohen et al. 1995, as cited by Behrens Yamada, unpublished manuscript). From this point on the California coast, the green crab expanded in both southerly and northerly directions along the U.S. west coast, and is presently found as far south as Morro Bay, California, and as far north as Lemmens Inlet near Tofino, Vancouver Island, British Columbia, where it landed in 1998 (Behrens Yamada, unpublished manuscript). **Figure 1** maps the areas on the U.S. west coast where the green crab has been found so far, along with the estimated dates of introduction. As one can see from this map, the northward expansion of the green crab has been much greater than the southward spread, despite prevailing southerly currents.

Although Cohen and Carlton (1995) state that green crabs have been found in virtually all types of protected and semi-protected marine and estuarine habitats, there is one interesting exception: on the U.S. west coast, green crabs have not normally been seen on exposed rocky shores, although they have been found in that habitat elsewhere in the world (Behrens Yamada, unpublished manuscript; Milne, personal communication).

Green crabs have arrived in Washington State

On June 9, 1998, in Washington's Willapa Bay, an employee from the state Department of Natural Resources and a scientist from California stumbled across one lone crab shell that did not look quite right. Unfortunately, it was confirmed to be the shell of a young, male European green crab. On the 21st of

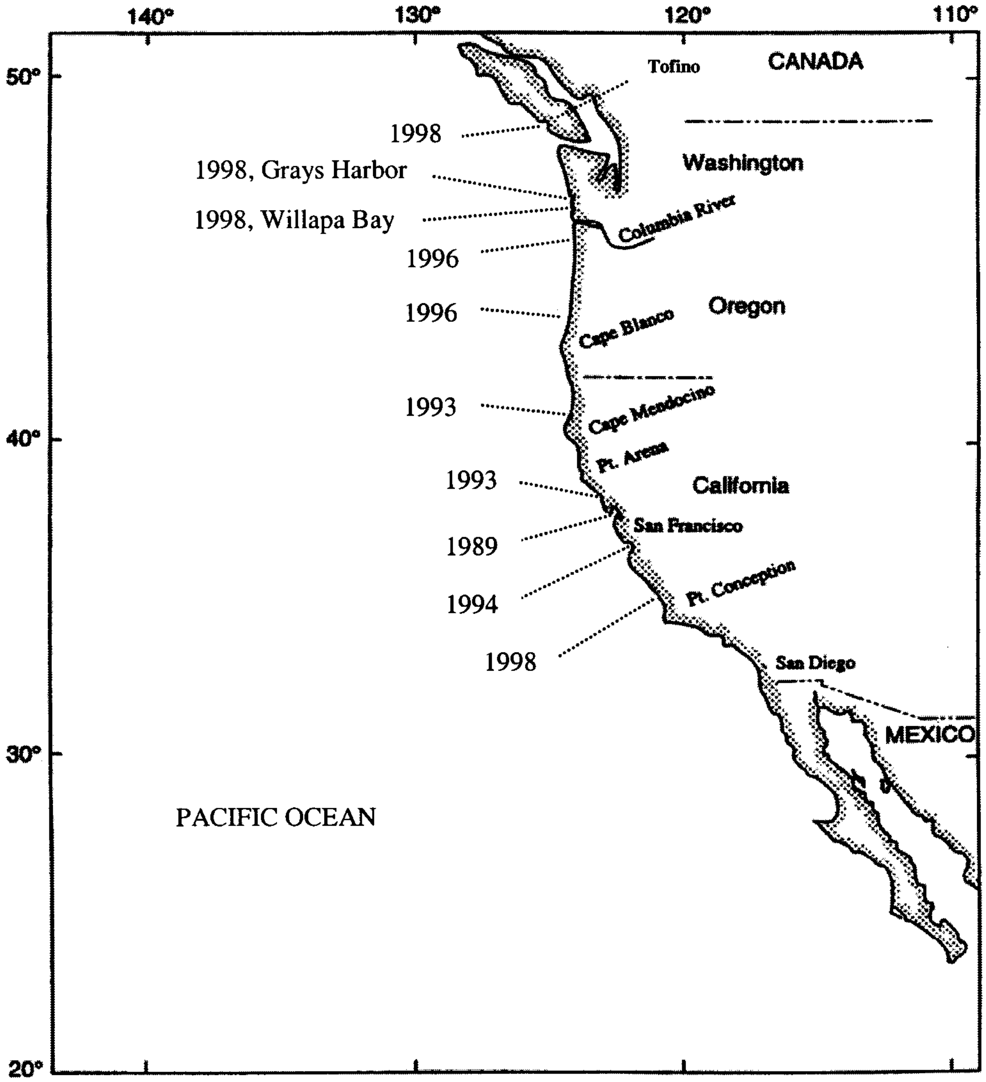

Figure 1. Estimated dates of introduction of the European Green Crab along the U.S. west coast. (Map modified from Behrens Yamada, unpublished manuscript)

July, the Washington Department of Fish and Wildlife (WDFW) announced that 11 green crabs had been captured that day in Grays Harbor. And so, the fight was on.

It is currently believed that the green crab's vector of introduction to Washington State was "most likely a matter of simple larval transport" (Dumbauld, personal communication). Ocean currents flowing northward from California and Oregon, the source regions of the west coast green crab population, were thought to have been especially good in facilitating transport of the crab larvae that year. Though probably related to the El Niño event of 1997-98 (Behrens Yamada, unpublished manuscript), which is a somewhat less-than-common occurrence, the fact remains that the crabs are now in Washington. On February 5, 1999, the first discovery of a female green crab with eggs—by a local oyster grower in Willapa Bay—was made, proving that green crabs are indeed breeding in Washington's bays (Washington Department of Fish and Wildlife 1998-2000b).

Green crabs have been found in Washington's two major coastal bays, Willapa Bay and Grays Harbor (see **Figure 1**). Although the Puget Sound region is only being monitored for any potential newcomer crabs at this point in time, trapping programs coordinated and run by the Washington Department of Fish and Wildlife were promptly set up in the two coastal bays as soon as the green crab was detected in those regions (Dumbauld, personal communication). As of the end of the year 2000, 796 live green crabs had been collected at Willapa Bay, and 230 in Grays Harbor, where the trapping was less extensive (Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b). Declines in the catch have been noted since 1998. It is unknown whether this is due more to the state's trapping programs or to lack of substantial new recruitment (Dumbauld, personal communication), but most likely it is a combination of both (Rogers 2001a).

Ironically, Dumbauld (personal communication) indicates that the presence of green crabs is highly correlated with the presence of *Spartina alterniflora*, the invasive cordgrass so prevalent in Washington's Willapa Bay. This is probably not surprising, given the fact that green crabs have been associated with tidal salt marshes (along with shellfish beds), habitats where *Spartina* also flourishes and where larger native crabs like the Dungeness crab are less abundant (Dumbauld, personal communication; Washington Department of Fish and Wildlife 2001a).

<u>Physical characteristics of green crabs</u>

In spite of their name, green crabs are not consistently green. They vary in color, which may change from green to orange and then red during molting cycles. Yellow, orange, and red coloration may be displayed on the underside of the green crab. Because of these color variations and the fact that many native crabs can be green, it is generally not a good idea to use color as a distinguishing characteristic when attempting to identify green crabs (Washington Department of Fish and Wildlife 2001a).

For simplicity in describing European green crabs, they have been further placed into two groups associated with color phase: green crabs and red crabs (Kaiser et al. 1990, as cited by McKnight et al. 2000). Red-colored individuals, which tend to be bigger, have been found to prefer larger bivalves, exert more force with their crusher claws, and win more disputes over prey than the green-colored version of the European green crab (Kaiser et al. 1990, as cited by McKnight et al. 2000; McKnight et al. 2000; Washington Department of Fish and Wildlife 2001a).

Five evenly spaced triangular teeth, or spines, are found on each side of the green crab shell, or carapace, behind the eye (see **Figure 2**). This feature sets the green crab apart from native crabs, which all have fewer than five, or more than five, teeth in this region. In addition, *Carcinus maenas* exhibits three rounded lobes or bumps between the eyes (Washington Department of Fish and Wildlife 2001a; see **Figure 2**). Green crabs may resemble juvenile Dungeness crabs (*Cancer magister*) in shape; again, the primary way of distinguishing the two is by spine count, since the juvenile Dungeness will have ten smaller spines on each side of the carapace (Behrens Yamada, unpublished manuscript). The native crab most confused with the green crab in Washington State is the helmet crab, *Telmessus cheiragonus*. Although helmet crabs are frequently green, it

Figure 2. Adult European green crab (*Carcinus maenas*). Note the five identifying spines on either side of the carapace, as well as the three lobes between the eyes. (Photo by Liz Carr, Washington Department of Fish and Wildlife)

should be noted that they have six, not five, spines on either side of the eyes; they also possess bristly antennae and sport a body covered with stiff hairs (Washington Department of Fish and Wildlife 2001a).

When measuring the size of a crab, the width of the carapace is typically noted. A typical adult green crab has a carapace width of 2.5 inches (64 mm), but crabs as large as 4 inches (about 100 mm) have been found in their native range in Europe. Here in Washington, captured green crabs have measured from 0.74 inches (19 mm) to 3.5 inches (90 mm) (Washington Department of Fish and Wildlife 2001a). In a molt increment study done on the green crab in Oregon, Behrens Yamada et al. (2000) report that green crabs at that location have fairly high growth rates. They also postulate that, unfortunately, green crabs grow larger in Oregon than in places like Maine or the North Sea, and that this may be due to more favorable temperatures on the U.S. west coast.

The sexes may be distinguished outwardly in two ways. Unless immature (smaller than 15 mm), the abdomen of males is more triangular in shape, whereas the female green crab's abdomen is broader and rounder. Additionally, green crabs larger than 30 mm react differently upon being picked up. Male green crabs typically stretch out their claws and legs, where females usually fold their appendages in closer to the body, a behavior that has been called the egg-protection reflex (Behrens Yamada, unpublished manuscript).

Reproduction and life cycle

Male green crabs molt more often and grow larger than females; they typically mate with females smaller than themselves. In the North Sea and Maine, mating primarily occurs from June (North Sea) or July (Maine) until October. Most European green crabs extrude eggs in the spring (Washington Department of Fish and Wildlife 2001a). Green crabs are quite prolific; females spawn up to 185,000 eggs at a time under favorable conditions (Cohen and Carlton 1995).

The new larvae aggregate in surface waters during the ebb tide at night, when current velocities are at their highest. After a two-week period of growth and development in the open sea, individuals in the crab's last larval stage aggregate at night in surface waters during flood tides. This last stage (megalops) then molts and settles out as a juvenile crab in upper intertidal zones (Washington Department of Fish and Wildlife 2001a).

Green crabs reach maturity within two to three years, and may breed up to three times per year. As green crabs age, they increasingly move from the intertidal to the subtidal zones. Eventually, the oldest crabs live more or less permanently in subtidal areas. The European green crab's minimum generation time is three years, and the maximum life span, at least in native ranges, is five years (Behrens Yamada, unpublished manuscript; Washington Department of Fish and Wildlife 2001a).

Deleterious ecological effects of green crabs

According to both field observations and laboratory experiments, *Carcinus maenas* eats a vast array of organisms from at least 104 families and 158 genera, in 5 plant and protist and 14 animal phyla (Cohen and Carlton 1995). Prey includes clams, oysters, snails, other crabs, polychaetes, isopods, barnacles and algae. In its native range, the green crab has a great impact upon populations of mussels, dogwhelks, and cockles (Washington Department of Fish and Wildlife 2001a). In a study done in Nova Scotia, Canada, Singh (1991) indicates that the crabs' diet in the intertidal zone of Crow Cove, Bay of Fundy, consists of molluscs (especially bivalves and periwinkles) and crustaceans (especially barnacles). At that location, as elsewhere, green crab dietary habits vary. This may depend on the frequency and amount of prey available (Singh 1991). Not only does the green crab have a great capacity for devouring diverse prey, but other species living in marine environments may have to compete with the green crab for food. These competitors may include native fish and birds (University of Washington 1999-2001), as well as other crabs.

Since the arrival of green crabs in California, native shore crab populations there have dropped significantly (Washington Department of Fish and Wildlife 2001a). Grosholz (1997) has shown that the yellow shore crab, also called the hairy Oregon shore crab (*Hemigrapsus oregonensis*), exhibited a "significant tenfold decrease in abundance" in Bodega Harbor from 1994-96. The declines show a significant negative association with the increasing abundances of green crabs. This should, unfortunately, come as no surprise. The Dungeness crab (*Cancer magister*) and the yellow shore crab, both native residents of the Pacific Northwest, may be consumed at up to the green crab's own size (Cohen et al. 1995; Grosholz and Ruiz 1995, as cited by Cohen and Carlton 1995). Predation, however, is certainly not the only, or even main, reason for native crab population declines. In the laboratory, Jensen et al. (2000) and McDonald et al. (2001) performed experiments in which they forced green crabs to compete with Dungeness and yellow shore crabs of similar size for both food and shelter. Although yellow shore crabs were able to outcompete green crabs for shelter, green crabs did indeed outcompete Dungeness crabs in this arena. And when it came to food, green crabs were consistently able to outcompete both of the other species, reaching and devouring the food sources first. Behrens Yamada (unpublished manuscript) suggests that, due to more complex factors in the field, these results should be interpreted carefully. However, she notes that these laboratory experiments may serve as indications of "...where the green crab fits into the dominance hierarchy of the native crab guild" (Behrens Yamada, unpublished manuscript). Green crabs have also been observed to kill the native red rock crab, *Cancer productus* (Wiegardt, personal communication), although Hunt and Yamada's (2001) laboratory studies report that red rock crabs are generally more aggressive and will prey upon green crabs of smaller, and occasionally equal, size. Hunt (2000) supports this last statement by observing that there is a scarcity of green crabs found in abundant *C. productus* territory.

Native clam populations have also dropped significantly since green crabs arrived in the State of California. For instance, studies have shown a significant reduction in populations of native small clams, *Nutricola* (=*Transennella*) spp., in habitats such as Bodega Bay, California (Cohen and Carlton 1995). Grosholz (1997) reports that two species of *Nutricola* exhibited tenfold decreases in abundance there from 1994-96; the declines show a significant negative association with the increasing abundances of green crabs. In a study done at one shellfish operation in Tomales Bay, California, the Manila clam (*Tapes philippinarum*) harvest showed a 40% drop after the arrival of green crabs (Biocontrol News and Information 1999; Grosholz and Olin 2000). Though the Manila clam is a long-established exotic species itself, its hardiness apparently does not make it immune to the dietary advances of the European green crab. Additionally, Lafferty and Kuris (1996) believe that the green crab is likely to cause major destruction to several *Macoma* clam and marsh mussel populations (among others) in the future.

The green crab serves as interim host to the acanthocephalan worm *Profilicollis botulus*, an endoparasite of shorebirds (Liat and Pike 1980), thus posing yet another potential impact on ecosystems in Washington. For example, the common eider (eider duck), *Somateria mollissima* (native to Scotland, North

America, and Asia) acquires *Profilicollis botulus* by eating infected green crabs (Rayski and Garden 1961, as cited by Thompson 1985; Rogers, personal communication). In a study done on the transmission dynamics of *Profilicollis botulus*, Thompson (1985) reports that the parasite's eggs are passed into the external environment through the common eider's feces. These eggs, in turn, infect green crabs, which then host the parasite's long-lived infective stage, called a cystacanth. Upon eating a green crab, the common eider also ingests the cystacanths, and the cycle repeats itself. Though common eiders would need to ingest larger crabs and eat them more frequently in order to seriously threaten the common eider population, Thompson (1985) states that this is a real possibility, depending on the availability of other prey for the ducks, and also states that "...this may be one of the mechanisms by which an epidemic is produced" (Thompson, 1985). In British Columbia, the Canadian province immediately to the north of Washington State, Ching (1989) has found that *Profilicollis botulus* parasitizes diving ducks. In that region, the native shore crab *Hemigrapsus oregonensis* acts as interim host to *P. botulus*. With regard to the European green crab, *P. botulus* has been found in these crabs not only in Scotland, but also in Russia and on the eastern shores of North America (Behrens Yamada, unpublished manuscript). The potential for *Profilicollis botulus* to enter and disrupt environmental systems in Washington State via the green crab should be taken as a serious threat.

Green crabs are capable of learning and are able to improve their prey-handling skills while foraging. They are also not only quicker, but are able to open shells in more ways, than other crabs (Washington Department of Fish and Wildlife 2001a). The rear legs of the green crab are adapted for running across mud, "...something it does with a certain amount of elegance and at relative lightning speeds," according to Rogers (2001a). Lee Wiegardt, a longtime oyster grower in Nahcotta, Washington, reports that he has even observed green crabs standing on their hind legs, presumably for increasing their visibility (Wiegardt, personal communication). He has also observed that, after molting, green crabs develop a hard shell much faster than many other crabs, a factor that would make them less vulnerable to predators. These and other traits have earned *Carcinus maenas* the title of "the working-man's crab" from Mr. Wiegardt. Though not a large crab, pound for pound, green crabs can outcompete and outmaneuver other crabs with ease. It is easy to see that they may constitute a significant threat to other organisms in their environment, and have the potential to easily disturb balances of existing ecosystems.

Deleterious economic effects of green crabs

It appears that aquaculture in Australia has not yet experienced significant impacts from the region's green crab invasion, but since the arrival of the green crab in Tasmania around 1993 (Proctor and Thresher 1997), worries have started to surface that appear similar to worries found on the U.S. west coast. Some research has been done; for instance, Walton (1997b) has done a preliminary evaluation of potential *Carcinus maenas* impacts upon the fishery for *Katelysia scalarina*, the native Tasmanian clam. He suggests that green crabs may indeed have a very large impact upon the abundance and distribution of *K. scalarina*, and thus upon the fishery.

In Canada, discussion about potentially negative economic effects of a green crab invasion has ensued in British Columbia, Washington's neighbor to the north. The shellfish aquaculture industry in British Columbia is currently based on three species: the Pacific oyster (*Crassostrea gigas*), Manila (Japanese littleneck) clam (*Tapes philippinarum*), and the Japanese weathervane scallop (*Patinopecten yessoensis*). Cultures of the blue mussel (*Mytilus edulis*), Mediterranean mussel (*Mytilus galloprovincialis*), geoduck (*Panopea abrupta*), and Pinto abalone (*Haliotis kamtschatkana*) are either being developed or are in early stages of production (British Columbia Shellfish Growers Association 2001). According to the University of Victoria (2000), the latter four species have great potential for increased production value. According to 1998 figures, the annual wholesale value of the shellfish industry in British Columbia is about $15 million, but it is estimated to be capable of producing $100 million per year. This could have positive implications for depressed coastal communities. However, a 2000 workshop report states that the threat of exotic species—the only one it names specifically is *Carcinus maenas*—may be of equal or even greater importance than the threat of global climate change to this Canadian industry either now or in the future (University of Victoria 2000).

Carcinus maenas is thought by many to be responsible for the destruction in the 1950s of the soft-shelled clam fisheries in New England and Canada (Cohen et al. 1995). In 1938, New England fishermen brought in 14.5 million pounds of the soft-shelled clam *Mya arenaria*, a record high. By 1959, that number had dropped to an abysmal 2.3 million pounds, hurting the region and thousands of people economically. During these same years, the range of the green crab expanded, and many attribute the decrease in clam catches, at least in part, to this invasion (Welch 1968, as cited by Behrens Yamada, unpublished manuscript). The population explosion and range expansion of the green crab can be correlated with the rise in ocean temperatures around the turn of the twentieth century (Rogers 2001a). If this trend holds true on the U.S. west coast, the green crab problem can only be exacerbated by predicted climate changes.

Additional impacts by the green crab have been felt on North America's east coast. The quahog (*Mercenaria mercenaria*), an edible clam also known as the hard-shelled or round clam, has decreased in numbers, as has the blue crab (*Callinectes sapidus*). The green crab is thought to be responsible for both of these declines (Rogers 2001a). Bay scallops (*Argopecten irradians*) are also a favorite food of green crabs, and residents along the U.S. east coast in Martha's Vineyard, Massachusetts, have actually instituted bounty programs on green crabs in order to try to decrease their scallop losses (Fincham 1996; Walton 1997a).

Because the green crab has not been a resident on the U.S. west coast for long, there are fewer documented examples of its destructive impacts on the aquaculture industry. But some scientists like Lafferty and Kuris (1996) believe that the green crab is likely to devastate subtidal and intertidal beds of species such as the soft-shelled clam (*Mya arenaria*) and the Manila (Japanese littleneck) clam (*Tapes japonica*) in places such as San Francisco. Scientists can only guess the impacts *Carcinus maenas* could have in Washington, based in large part upon results of experimentation with green crabs and other organisms in the laboratory. These studies provoke concerns about the green crab's potential economic impacts. For instance, laboratory studies have confirmed that the green crab preys upon organisms such as the California mussel (*Mytilus californianus*), Mediterranean mussel (*M. galloprovincialis*), and blue mussel (*M. edulis*), which are found in large numbers along the U.S. west coast (Cohen and Carlton 1995; Sheldon 1998). Additionally, studies done outside the laboratory have already indicated downward trends in harvest rates; recall the study done in Tomales Bay, California, which showed a 40% drop in one operation's Manila clam harvest after green crabs arrived in that area (Biocontrol News and Information 1999; Grosholz and Olin 2000). Shellfish appear to be immune to green crab predation when they reach a certain size—60 mm for oysters and 45 mm for mussels—but it is the smaller-sized shellfish and seed stocks that will suffer. The Washington Department of Fish and Wildlife (2001a) states that nearly three dozen mussels under 45 mm in length may be eaten daily by a green crab. Wilhelm (2000) alleges that one green crab can eat more than 40 young shellfish per day.

Statements such as this evoke alarming scenarios for the future of commercially important marine organisms.

Estimates of the value of the Washington State shellfish industry (which includes both the coast and Puget Sound) vary, but it is worth at least an annual \$40 million. Some estimates place it as high as \$100 million annually (Rogers 2001a). People for Puget Sound (1996) reports a figure of \$65-\$70 million total commercial harvest in Washington for the year 1993. The British Columbia Shellfish Growers Association (2001) states that Washington's shellfish culture industry is estimated at greater than \$60 million annually; Wilhelm (2000) cites the Washington shellfish industry as currently generating \$73 million in revenue per year, and employing approximately 2,000 people. One analysis estimates that each job in the oyster industry supports 1.13 additional jobs elsewhere in the state economy (People for Puget Sound 1996). If we apply this figure to the shellfish growers in Washington, approximately 4,260 jobs are currently related to the shellfish industry in this state. Many of these jobs are a significant employment base and show long-term, sustainable economic growth for rural and distressed communities. The oyster industry in Puget Sound is one of the two most significant sources of commercial oysters in the nation, and overall, Washington State is "...the largest producer of cultured clams and one of the top two producers of cultured mussels in the western United States" (People for Puget Sound 1996).

The Washington Department of Fish and Wildlife (2001a) states that it believes the green crab will pose significant threats to the state's clam, oyster, and mussel industries if it ends up becoming established in Washington waters. As is the case in British Columbia, Washington State shellfish growers are already worriedly discussing potential green crab impacts amongst themselves. Lee Wiegardt, an oyster grower with 11,000 feet of shoreline in western Washington State, reports that *so far* he does not know of any local oyster growers that have suffered problems or damage due to green crab predation. However, the number of green crabs that have been discovered in Washington is still small, and oyster growers are anxious about larger numbers having potential impacts on their businesses. Wiegardt notes that green crabs appear to go after Manila clams first ("the crabs would rather eat caviar than peanutbutter"), but he also worries about what could happen if clam populations decrease and the green crab expands its tastes (Wiegardt, personal communication).

Puget Sound, in particular, is a very productive bivalve shellfish-growing area. The Puget Sound Water Quality Action Team (2000) reports that the Puget Sound shellfish industry produced 50 million pounds live weight of bivalve shellfish (clams, oysters, and others) in 1998. This translates to a wholesale value of $50 million for that year, with 140,000 acres of commercial shellfish acreage in production. People for Puget Sound (1996) estimates that Puget Sound shellfish growers brought in about half of the $65-$70 million harvested statewide in 1993.

Annual shellfish production in Puget Sound has been increasing in past years, and more than doubled from the years 1979 to 1993.

As previously mentioned, green crabs have not yet been spotted in Puget Sound. This is fortunate because, among other things, the last 20 years have seen increased restrictions on shellfish harvesting due to pollution and high levels of fecal coliform (People for Puget Sound 1996). Because of the concentration of shellfisheries in the Puget Sound area, it is economically essential that the State of Washington not only maintain its current coastal trapping programs in order to inhibit a green crab spread, but it is also essential to continue the monitoring efforts that are presently taking place in the Sound itself. If green crabs are detected early (and pursued), the aquaculture industry will have a much greater chance of maintaining their current catches, an already somewhat difficult task due to water quality issues. Additionally, in the event of an influx of green crabs, early detection allows shellfish growers to have more time to mount defenses against the green crab. These tactics can include surrounding shellfish beds with more appropriate fencing, using small-meshed nets, covers or bags, or adjusting the time of planting seed stocks, a viable option if settlement rates of green crabs are known (Behrens Yamada, unpublished manuscript). The fact that the commercial shellfish industry deems these issues important should be one of the deciding factors in whether the Washington State legislature decides to keep current funding in place, and whether they decide to increase such funding.

Besides the shellfish industry, the green crab could have a major impact on both the Dungeness crab (*Cancer magister*) and flatfish fisheries, such as that for the English sole (*Pleuronectes vetulus*). These two Pacific Northwest fisheries are collectively valued at $130-$135 million coast wide, roughly split between Oregon and Washington (Rogers 2001a; Rogers 2001b). The Dungeness crab is a commercially valuable species in the State of Washington. As a popular catch and preferred seafood dish, the State of Washington works to protect Dungeness crabs from over-exploitation by prohibiting all but male crabs larger than 6.5 inches (17 cm) from being taken (Sheldon 1998). As mentioned earlier, green crabs may eat Dungeness crabs at up to their own size, and thus have the potential to wipe out vast numbers of younger Dungeness crabs before they even have the chance to reach a commercially viable threshold.

<u>Additional impacts upon biodiversity in Washington State</u>

I have found little discussion on how a green crab invasion might affect non-commercial species in the Pacific Northwest, especially those that are species of concern (a term I use here in a general sense). In its July 1999 publication *Priority Habitats and Species List*, the Washington Department of Fish and Wildlife provides an outline of species that the state considers to be of priority for management and preservation. Included in this list are several gastropods and bivalves, and two crustaceans. Since these priority species are rarely included in current discussion or literature addressing potential green crab outbreaks, I have included a discussion of them here.

A list of Washington species of concern that are potentially vulnerable to a green crab invasion may be found in **Table 1**. These listings have been taken from the *Priority Habitats and Species List* (Washington Department of Fish and Wildlife 1999a). I have included only those species that are potential food sources for the green crab. I decided upon this particular list after reviewing the dietary intakes and habits of green crabs, both in the United States and elsewhere.

The priority species found in **Table 1** include state listed species (endangered, threatened, or sensitive), state candidate species (to be reviewed by the Washington Department of Fish and Wildlife for possible listing), species that occur in vulnerable aggregations (susceptible to significant population declines), and species of recreational, commercial, and/or tribal importance that are vulnerable (Washington Department of Fish and Wildlife 1999a). Each category is numbered for easy referencing in the table.

The first species on the list, Newcomb's littorine snail (*Algamorda subrotundata*, also classified as *Algamorda newcombiana* and *Littorina subrotundata*), is a Washington State Candidate species (to be reviewed by Washington Department of Fish and Wildlife for possible listing as Endangered, Threatened, or Sensitive), and a Federal Species of Concern as well (Washington Department of Fish and Wildlife 2000a). As can be seen in **Table 1**, it congregates in vulnerable aggregations that are susceptible to significant

Common Name	Scientific Name	Priority Species Criteria	Priority Areas
Newcomb's littorine snail	*Algamorda subrotundata*	1, 2	Any occurrence*
Pinto (Northern) abalone	*Haliotis kamtschatkana*	1, 2, 3	Any occurrence
Geoduck clam	*Panopea abrupta*	2, 3	Regular and regular large concentrations**
Butter clam	*Saxidomus giganteus*	2, 3	Regular and regular large concentrations
Littleneck clam	*Protothaca staminea*	2, 3	Regular and regular large concentrations
Manila clam	*Tapes philippinarum*	2, 3	Regular and regular large concentrations
Olympia oyster	*Ostrea lurida*	1, 2, 3	Any occurrence, regular and regular large concentrations
Pacific oyster	*Crassostrea gigas*	2, 3	Regular and regular large concentrations
Razor clam	*Siliqua patula*	2, 3	Regular and regular large concentrations
Dungeness crab	*Cancer magister*	2, 3	Breeding areas, regular and regular large concentrations

1 = State Listed species (Endangered, Threatened, or Sensitive) or State Candidate species (to be reviewed for possible listing)
2 = Vulnerable aggregations (susceptible to significant population declines)
3 = Species of recreational, commercial, and/or tribal importance that are vulnerable

* Any occurrence means that either the species is rare, or its limiting habitats are not known.
** Regular concentrations are defined as areas that are commonly or traditionally used by a group of animals on a seasonal or year-round basis. Regular large concentrations are defined as areas that are commonly or traditionally used by significantly large aggregations of animals, relative to what is expected for a particular species or geographic area.

Table 1. Washington priority species (Washington Department of Fish and Wildlife 1999a) potentially vulnerable to the European green crab.

population declines. This small marine snail, which sports a thin, conical shell, is typically found clinging to rocky shores in the upper intertidal zone. Its greatest threats are habitat loss and introduced species such as the green crab (Pacific Biodiversity Institute 2001). Thought to live on pickleweed (*Salicornia virginica*) in Willapa Bay's native saltmarsh (Washington Department of Fish and Wildlife 1995), Newcomb's littorine snail may already be experiencing habitat loss as a result of *Spartina alterniflora* crowding out native vegetation such as pickleweed. A larger incoming population of green crabs may be all it takes to push this snail population to the point of no return.

The Pinto (Northern) abalone, occasionally called the Japanese abalone (*Haliotis kamtschatkana*), is a Washington State Candidate species as well. It, too, falls into the "vulnerable aggregations" category found in the *Priority Habitats and Species List*. This marine mollusc is the smallest of abalones, reaching a maximum length of 6-7 inches (18 cm). These abalones are usually found clinging to rocks in kelp beds between the low intertidal zone and 18 m depth. Mortality rates of larvae and young adults are extremely high, and their thin shells are easily damaged, leaving them vulnerable to predators. Commercial overharvesting from 1975 to 1990 drastically reduced Pinto abalone populations. Since then, harvesting of the species has been banned over much of its range, which runs from California to Alaska. Recreational harvesting within Washington was closed in 1994, but along with habitat loss, poaching continues to pose a serious threat to recovering populations (Pacific Biodiversity Institute

2001; Sheldon 1998). The additional threat of an invasive species could easily add to the Pinto abalone's dismal outlook.

Geoduck clams (*Panopea abrupta* or *Panope generosa*), though they may seem invulnerable because of their large size, are listed in the "vulnerable aggregations" category and are thus susceptible to significant population declines, as are all clams and oysters listed in **Table 1**. Living up to almost 150 years, the geoduck has been threatened by overharvesting. At the age of 6-7 years, this clam is of harvestable size (Sheldon 1998). Regulations are enforced against the taking of younger geoducks, but the youngest geoducks are those to which the green crab poses a threat.

Three hard-shelled clams have also made the priority species list. The butter clam (*Saxidomus giganteus*), also known as the smooth Washington clam, is the mainstay of the clam industry. Regulations are in place to keep smaller clams from being taken; this allows the populations to sustain themselves (Sheldon 1998). However, it is these same smaller-sized clams that are most at risk of being preyed upon by the European green crab.

The littleneck clam (*Protothaca staminea*) goes by several different common names, including native littleneck, rock cockle, common Pacific littleneck, and steamer clam. The minimum size harvestable by law tends to be around 1.5 inches, or 38 mm (Sheldon 1998). Adding to its troubles of displacement by the exotic Manila (Japanese littleneck) clam, this native clam is also a potential food source for the green crab.

The Japanese littleneck (*Tapes philippinarum*, *Tapes japonica*) clam's most frequently used common name is the Manila clam, although it too is sometimes known as the steamer clam (see above, *Protothaca staminea*). This intentionally-introduced clam from the west Pacific Ocean has become common in waters of the Pacific Northwest, and has frequently displaced the native littleneck clam (Sheldon 1998). Manila clams are now listed as being capable of having vulnerable aggregations susceptible to significant population declines. Sheldon (1998) reports that huge numbers can be killed by cold winters. It has been shown that green crabs eat Manila clams in both the field and the laboratory (Cohen et al. 1995; Grosholz and Ruiz 1995, as cited by Cohen and Carlton 1995; Grosholz and Olin 2000). Wiegardt (personal communication) also reports seeing green crabs go after Manila clams as a favorite food source. This could obviously spell trouble for the large Manila clam industry in Washington and British Columbia. The Washington Department of Fish and Wildlife (2001a) states that the green crab will pose a "significant threat" to the state's clam and oyster-growing industries if it ends up becoming established in Washington waters; this is not only an important issue economically, but one can see that it also poses a threat to the balance of existing ecosystems in the state.

The Olympia oyster, *Ostrea lurida (=conchaphila)*, is another species that is listed as a State Candidate species in Washington, in addition, of course, to falling into the "vulnerable aggregations" category. This shellfish, Washington State's only native oyster, has been displaced in large part by the non-native and larger Pacific oyster (*Crassostrea gigas*). Once abundant along the U.S. west coast, it has now disappeared from much of its original range (Sheldon 1998). Overharvesting significantly depleted stocks in Willapa Bay and Puget Sound by the 1870s. In addition, the Olympia oyster is sensitive to pollutants, particularly pulp and paper mill effluent, and these pollutants played another large part in its decline, particularly before the 1950s when the industry was unregulated. When oystermen began to enhance their ailing native stocks by bringing in the Pacific oyster, the Olympia oyster experienced further declines due to competition. Along with their Pacific oyster hosts, invasive species such as the Japanese oyster drill (*Ocenebra japonica*) and a parasitic flatworm (*Mytilicola orientalis*) were introduced (Pacific Biodiversity Institute 2001). Although reintroduction efforts are currently underway, the threat of another non-native species needs to be seriously addressed if we want to ensure that these restoration efforts will be successful and guarantee the survival of the Olympia oyster in Washington State.

Ironically, the Pacific oyster (*Crassostrea gigas*) has made the priority species list, in spite of the fact that it is originally an introduced species itself, as it is susceptible to significant population declines. Now the greatest contributor to the oyster industry, the Pacific oyster (also called the Japanese oyster) has been a victim of other introduced species such as the Atlantic oyster drill (*Ursosalpinx cinerea*) (Sheldon 1998).

Razor clams (*Siliqua patula*) are occasionally used effectively as bait when trapping green crabs (Washington Department of Fish and Wildlife 1998-2000b), so we can guess that green crabs at least enjoy the taste. Razor clams, once again, are a clam listed in the "vulnerable aggregations" category, and are protected from overharvesting by regulations prohibiting the taking of any clams under 4.5 inches, or 11 cm (Sheldon 1998). It should be noted that green crabs and razor clams may not always share the same habitat (personal observation), so it is possible the crabs might not be as much of a threat to razor clams as they are to the other species listed in **Table 1**.

Finally, the Dungeness crab, *Cancer magister*, has found its way onto the priority species list, being classified in the "vulnerable aggregations" category, as well as being a "species of recreational, commercial, and/or tribal importance that (is) vulnerable" (Washington Department of Fish and Wildlife 1999a). It is apparently for these reasons that the State of Washington regulates against the taking of any Dungeness crabs that are not male and at least 6.5 inches in size. As previously mentioned, green crabs can and do consume Dungeness at up to their own size, according to laboratory studies (Cohen et al. 1995; Grosholz and Ruiz 1995, as cited by Cohen and Carlton 1995). Since Dungeness crabs spend part of their early life in the intertidal zone, they may be at risk of predation by green crabs during that time (Washington Department of Fish and Wildlife 2001a). But this is not the only threat that *Carcinus maenas* poses to *Cancer magister*. Green crabs compete intensely with other crabs for food and shelter (Behrens Yamada, unpublished manuscript). Recall the McDonald et al. (2001) laboratory trials, where green crabs were matched with similarly-sized Dungeness crabs and forced to compete. Green crabs consistently beat Dungeness crabs not only to food sources, but they also won the race to sources of shelter.

As can be seen, a green crab influx could pose a serious threat to biodiversity in Washington State. When deciding whether or not to continue or increase monitoring, prevention, and control activities, this potential threat should be weighed heavily. Declines in sensitive populations are difficult and expensive to reverse. And if any of these priority species should disappear, they could easily be gone for good.

PREVENTING, DETECTING, AND CONTROLLING GREEN CRABS

Introduction

Washington State's response to the green crab invasion centers on both management and control of existing crabs, and avoiding new introductions. In Puget Sound and the Strait of Juan de Fuca, no green crabs have yet been found, and extensive monitoring is currently being done in order to detect any future problems. Meanwhile, in Willapa Bay and Grays Harbor, measures have been undertaken to reduce existing green crab populations. Whether the green crab population in those areas remains at current levels, decreases, or rises, it is important to look at different methods of green crab control (as well as detection and prevention) in various parts of the United States and other countries for possible adoption by Washington. Analyzing different methods of control will help us utilize feasible, pertinent methods that are most applicable toward European green crab control in our state. This section discusses what we already know and what further research needs to be done, and makes an attempt to determine if Washington State is making the best use of its sometimes scarce monetary resources in the war against *Carcinus maenas*.

Prevention measures

According to scientists and many policy makers, the best green crab plan focuses on avoiding introduction in the first place. It is therefore critical to institute and maintain prevention measures in Washington State. These measures can help to keep the green crab from spreading out of Willapa Bay and Grays Harbor. It is hoped that the green crab will never enter Puget Sound or the Strait of Juan de Fuca. However, those areas are at high risk, not only because of the coastal infestations, but also because green crabs have been found near Tofino, near Victoria, and in Barkley Sound (Behrens Yamada, unpublished manuscript). All these locations are on Vancouver Island, British Columbia, immediately to the north of Puget Sound.

Several important actions have recently been implemented in Washington State that are designed to prevent green crabs (as well as other invasive species) from spreading further into the state's waters, including Puget Sound and the Strait of Juan de Fuca. The first is the establishment of restrictions on the import and transfer of shellfish by the Washington Department of Fish and Wildlife (Rogers 2001a). This regulation prohibits the transfer of shells, shellfish, and aquaculture equipment from Willapa Bay or Grays Harbor to other Washington waters, unless permission is granted from WDFW (Washington Department of Fish and Wildlife 2001a).

The State of Washington has also enacted an emergency regulation (WAC 232-12-01701) that labels the European green crab a deleterious exotic species and prohibits persons from transporting and possessing any live green crabs without a special permit. Under no circumstances can green crabs be released to local marine waters (Washington Department of Fish and Wildlife 2001a).

Additional restrictions have been placed on imports from out-of-state. These include "...requiring one-hour chlorine dips for shellfish seed and broodstock from European green crab infested areas" (Washington Department of Fish and Wildlife 2001a). And as WAC 232-12-01701 states, "Live European green crabs may not be imported into Washington without first obtaining written permission from the director of WDFW" (Washington Department of Fish and Wildlife 2001a).

Finally, groundbreaking legislation was passed in the spring of 2000 that regulates the discharge of ballast water in the state, the Ballast Water Management Act (RCW 77.120). On September 22, 2000, Washington State began enforcing its first new ballast water rule. Among other things, coastal cargo vessels must now exchange ballast water at least 50 miles offshore and report the exchange. Vessels must file a ballast water management report at least 24 hours prior to discharging their ballast in Washington waters, the report being submitted to the Washington Department of Fish and Wildlife. After July 1, 2002, discharge of ballast water into Washington waters "...is prohibited unless it has been adequately exchanged or treated to meet standards to be set by the Washington Department of Fish and Wildlife" (Washington Department of Fish and Wildlife 2000b; Washington State Aquatic Nuisance Species Committee 1998). These measures greatly reduce the risk of green crab larvae hitchhiking into Washington in the hulls of ships and, of course, aid in preventing introductions of other exotic species. Washington is considered by some to be one of the most progressive states in trying to stop the spread of invasive species; the new ballast water management law is a good example of this. The law is only the second of its kind—California did it first—passed in the United States (Wilhelm 2000).

Early detection (monitoring)

Rogers (2001a) states that, once an area has been infested, the "only known method that holds promise" is early detection and subsequent removal of as many individuals as possible. He feels that this method is still a viable option for the coasts of Washington State, British Columbia, and Alaska.

In 1999, a large-scale green crab monitoring program was established, with the Washington Department of Fish and Wildlife as the coordinating agency, in the Puget Sound region. This monitoring program includes not only Puget Sound itself, but also the Strait of Juan de Fuca and the San Juan Islands (Washington Department of Fish and Wildlife 2001a). The headquarters for these coordinated activities are WDFW's Point Whitney Shellfish Laboratory in Brinnon, Washington, on the northwestern shores of Hood Canal. This program is detective in nature, and is also aimed at keeping green crabs from spreading into the Puget Sound region from Grays Harbor, Willapa Bay, British Columbia, and points unknown. The Puget Sound monitoring program is extensive. In the three years from 1999 to the present (2001), roughly 200 sites have been established at locations that are considered high-risk (Rogers 2001a; Sato, personal communication; Washington Department of Fish and Wildlife 1999e; Washington Department of Fish and Wildlife 2001a). **Figure 3** shows locations where monitoring has been done in Puget Sound, the San Juan Islands, and along the Strait of Juan de Fuca. The vast majority of these sites are still in existence.

Baited crayfish traps are set out at various monitoring points around the Puget Sound region, and are periodically checked for the presence of green crabs (Washington Department of Fish and Wildlife 2001a). Out of the approximately 200 sites established since the program's inception, 51 have been monitored exclusively by the Washington Department of Fish and Wildlife (Sato, personal communication; Washington Department of Fish and Wildlife 1999e; Washington Department of Fish and Wildlife 2001a). The major emphasis is on checking the traps from April to September, the months when green crabs are most likely to be found (Rogers, personal communication).

Adopt-a-Beach, a now defunct non-profit organization whose goals included maintaining healthy beaches in the region, was originally responsible for checking approximately 35-40 of the trapping sites, using volunteer members. These volunteers were trained by the Washington Department of Fish and Wildlife to set crayfish traps and check them for green crabs. Fortunately, when Adopt-a-Beach went under, most of these volunteers transferred their loyalties to

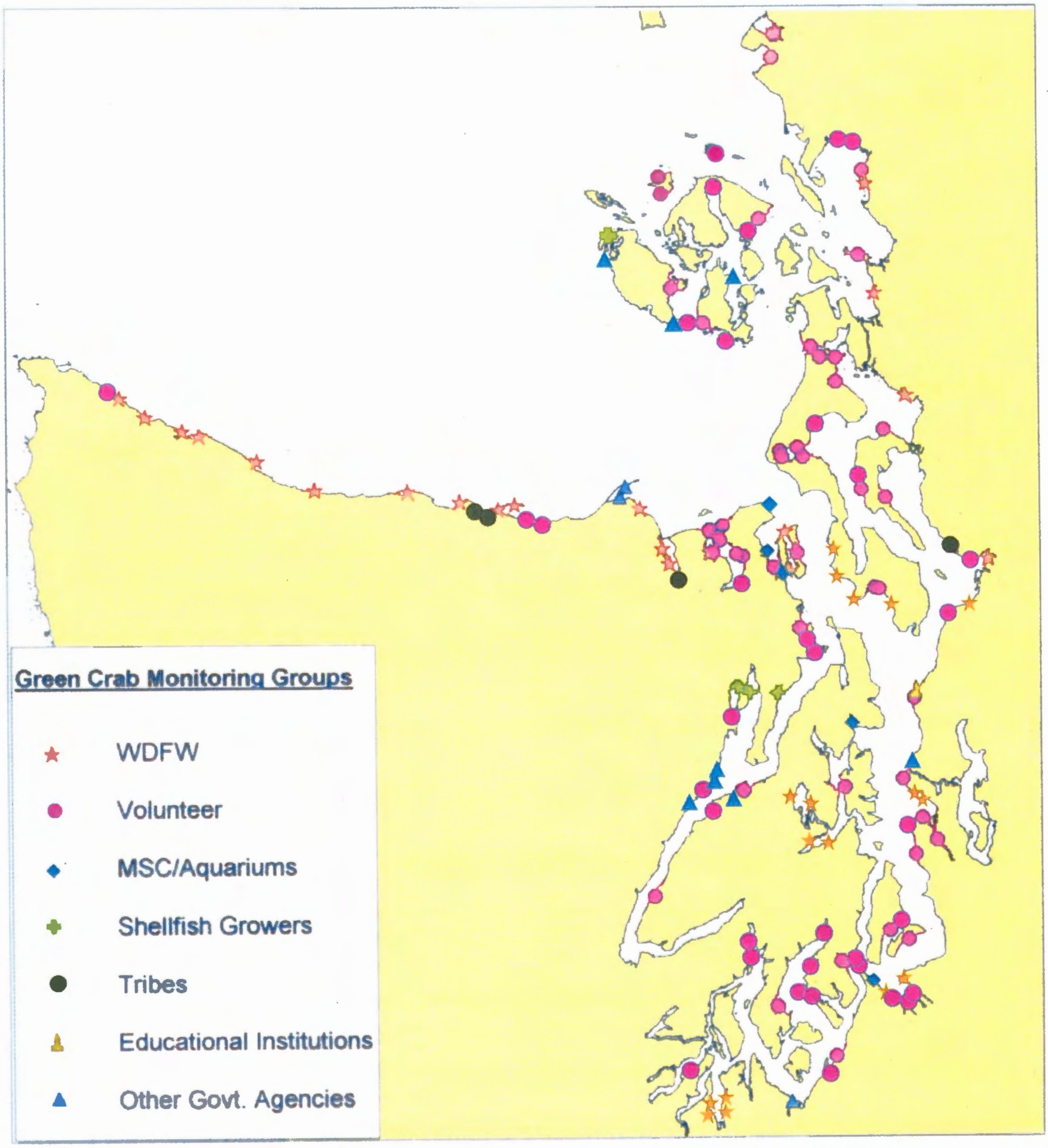

Figure 3. Representative monitoring sites for the European green crab in the Puget Sound region of Washington State, 1999 – 2001 (not all sites in heavily monitored areas included). MSC = Marine Science Center. (Map modified from Washington Department of Fish and Wildlife 1999e)

the Puget Sound Restoration Fund, which took over the effort. All site-checking activities formerly run by Adopt-a-Beach were thus largely kept intact. The Washington Department of Fish and Wildlife contracts with Puget Sound Restoration Fund on this effort, paying $6,000 a season (March - September) to a part-time employee at the Restoration Fund. The person in the part-time position is responsible for coordinating the checking of traps that Puget Sound Restoration Fund has now assumed responsibility for (Rogers, personal communication). Currently, approximately 30 of out a possible 60 monitoring sites are being checked by PSRF volunteers (Sato, personal communication).

The remainder of the approximately 200 total sites (about 110 over the last three years) have been checked by other government entities besides WDFW (county, state and federal), and individuals from local tribes, marine science centers, and schools, as well as additional volunteers that have included a handful of shellfish growers. All told, WDFW and other government employees have been responsible for approximately 65 sites in the last three years, with about 135 sites—over 67% of the total—being monitored by volunteer groups and individual volunteers (Sato, personal communication; Washington Department of Fish and Wildlife 1999e; Washington Department of Fish and Wildlife 2001a). The Washington Department of Fish and Wildlife in Brinnon coordinates these activities. There is a specific position at WDFW delegated for this task, that of the Puget Sound Monitoring Coordinator (Rogers, personal communication).

To date, no green crabs have been found in Puget Sound, the San Juan Islands, or the Strait of Juan de Fuca, at least not on the Washington side. One green crab has been found near Victoria, British Columbia, which is located on the Strait of Juan de Fuca's northern shore (Rogers 2001b).

Though state funding for continuation of green crab monitoring and control programs was previously in doubt, current funding levels will almost certainly remain in place for the July 2001 - June 2003 time period (Jacobsen, personal communication). It is commendable that the State of Washington is taking such a proactive stance. Not only is Washington maintaining funding for programs involving actual capture of existing crabs, but the state is also continuing a program that searches for new ones. Economically, this is a good choice, for common sense, as well as experience, tells us that it is least costly to head off non-native species invasions at the pass.

<u>Trapping</u>

The physical-control method of trapping is cited by Rogers et al. (2000) as the most environmentally sound and cost-effective option for the control of green crabs. However, it appears that not all crabs enter traps, so additional methods of control may sometimes need to be used (Rogers et al. 2000). Trapping has been used on North America's east coast; success there has been varied (Cohen et al. 1995; Walton 1997a).

The major method of green crab control in Washington State has been the use of traps. Success in trapping is measured in CPUEs, or catch per unit effort, and is determined by taking the number of crabs caught and dividing this number by the number of hours the traps were in place. The most effective, cost-efficient, and easily deployed traps are modified crayfish traps, which are set in lower intertidal areas around the perimeters of the bays (Rogers et al. 2000). These are used rather extensively in the Willapa Bay and Grays Harbor areas, the only places in Washington where the green crab has been found.

Pit-fall traps, which have a more permanent nature, are also used by WDFW, primarily at their long-term monitoring sites. They are made by digging a hole in the ground and dropping a 5-gallon bucket into the hole. Green crabs then fall into the traps and cannot get out. Pit traps have also proved to be quite effective in catching green crabs (Dumbauld, personal communication; Rogers et al. 2000).

More males than females are trapped, at least in the two Washington bays. This is probably partially due to two types of trapping bias. Male green crabs are more aggressive, and may get into crayfish traps first and then keep the females away. Also, males can potentially eat females and smaller crabs while in the traps. Because crabs cannot climb out of pit traps, the use of pit traps largely eliminates the first trapping bias, but cannot eliminate the second (Dumbauld, personal communication). Brooding females also have a tendency to avoid traps better than males (Sea Grant Oregon 2000).

Figure 4 shows the locations where green crab traps have been placed in the Willapa Bay and Grays Harbor areas, and indicates which sites have seen the capture of green crabs and which have not. The trapping program has been maintained by Washington State Department of Fish and Wildlife biologists since 1998. Since then, a steady decline in the numbers of crabs caught has been noted in both regions, as can be seen in **Figure 5**, which graphs the CPUE against years 1998 through 2000. However, it is uncertain how much of this is due to trapping measures, and how much to lack of recruitment and other factors. Most likely, it is a combination of variables (Rogers 2001a). An exception to the decline in number of crabs caught has been in the current calendar year, 2001. As of June, spring trapping results seemed to indicate the same number of green crabs being caught as in the spring of 2000 (Figlar-Barnes, personal communication). Further discussion of Washington's trapping program is included in the section "Population status," below.

Various types of bait are usually placed in the traps, with varying degrees of success. Fresh fish—such as mackerel—seems to work best, and is most often used by the Department of Fish and Wildlife (Rogers et al. 2000). Other baits that have been successful include whitefish, salmon, calamari, oysters, razor clams,

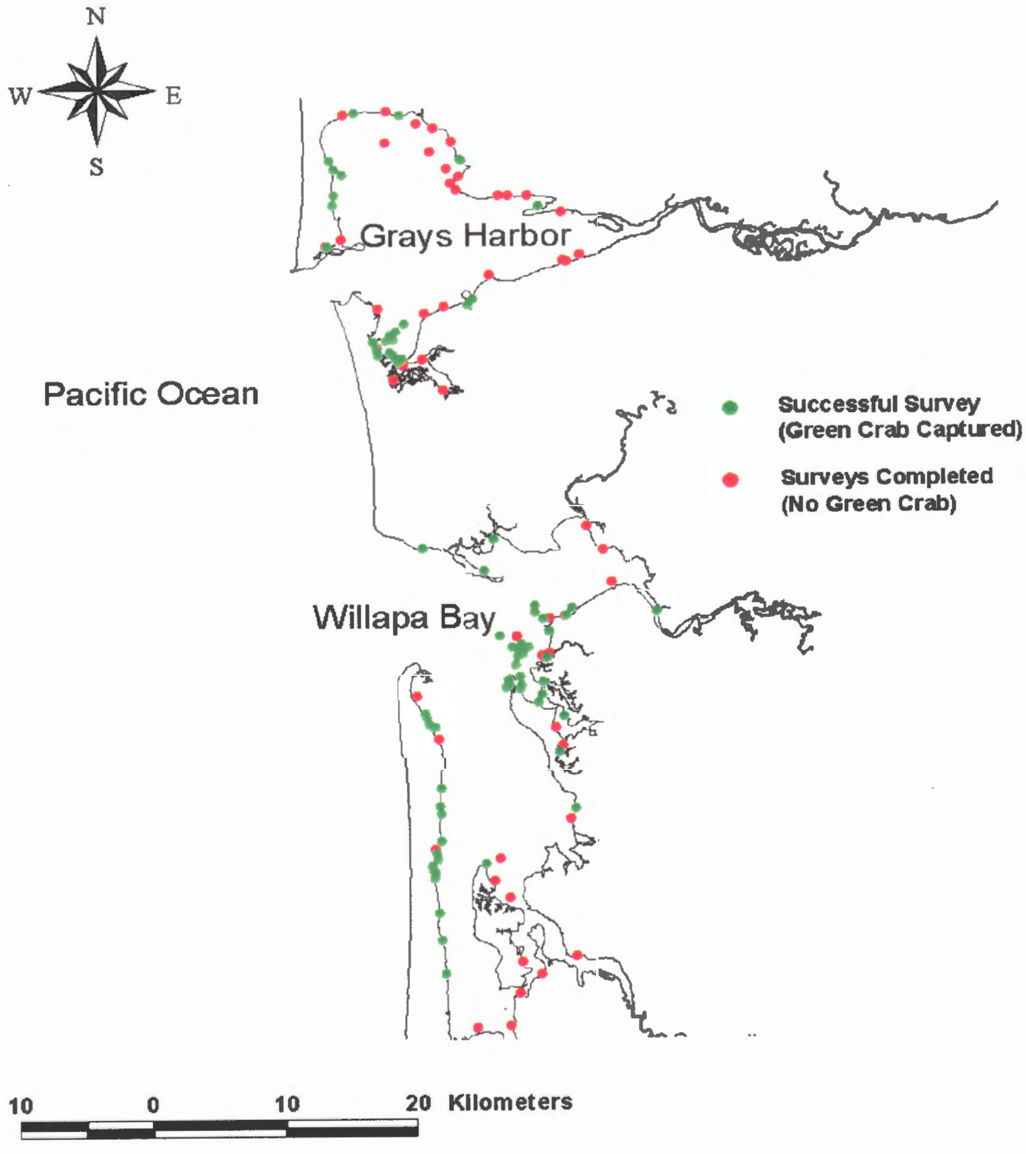

Figure 4. Washington Department of Fish and Wildlife green crab survey effort, Willapa Bay and Grays Harbor, Washington, 1998 – 2001. (Source: Washington Department of Fish and Wildlife 2001b)

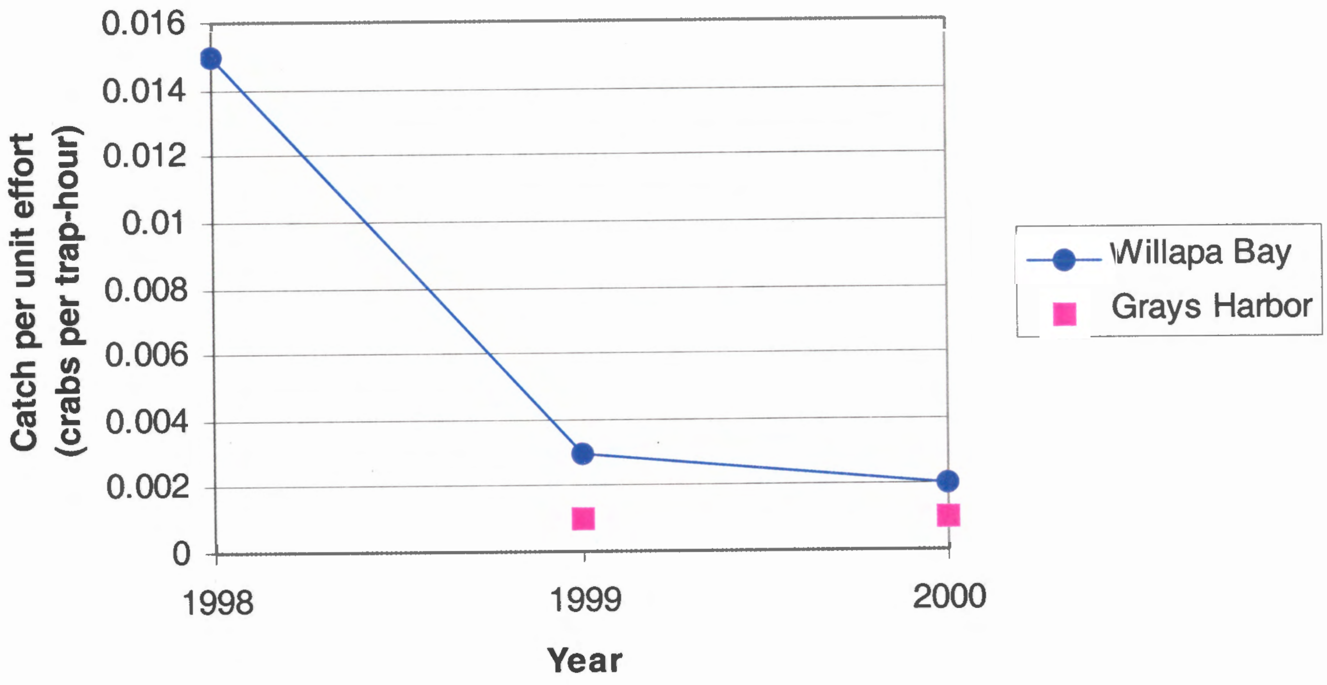

Figure 5. Catch per unit effort (CPUE) of European green crabs caught by the Washington Department of Fish and Wildlife in Willapa Bay, Washington, 1998 – 2000, and in Grays Harbor, Washington, 1999 – 2000. Grays Harbor data from 1998 unavailable. (Source of data: Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b)

mussels, and even cat food—which is the bait most often used in Puget Sound monitoring efforts (Rogers, personal communication; Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b).

Many local volunteers (usually property owners but also oyster growers, high-school students and college students) have pitched in to help WDFW check traps for the presence of green crabs (also see "Volunteer programs" section). The 2001 monitoring effort includes help from the Makah, Quileute, and Shoalwater tribes, as well as the Columbia River Estuary Task Force (CREST). These efforts will result in additional coastal surveillance (Washington Department of Fish and Wildlife 2001a), and may help to keep green crab populations down via additional trapping.

Although continued state funding for this program was in question earlier this year (2001), it is now believed that current funding levels will remain in place for the July 2001 - June 2003 time period (Jacobsen, personal communication). This is good news for the Washington Department of Fish and Wildlife, which has advocated that trapping efforts continue indefinitely or until no more green crabs can be found (Rogers 2001a).

If a detection does occur in the Puget Sound region, where no crabs have been found to date, the Department of Fish and Wildlife is prepared to launch an intensive trapping effort to control or eliminate those green crabs as soon as possible (Rogers 2001a).

Keeping crabs out of specific areas

Fencing is a physical control method that has been used in the fight against the European green crab. It is used to exclude green crabs from certain areas, thereby protecting shellfish and other organisms vulnerable to disturbance by the green crab. The fences, nets, or other materials need to be such that even small green crabs cannot crawl through them and into the shellfish areas. Fencing has been used in New England and Canada, with varying levels of success (Behrens Yamada, unpublished manuscript; Cohen et al. 1995). In Tomales Bay, California, mesh enclosures seem to be working successfully in reducing predation of green crabs on clam and oyster seeding operations (Lafferty and Kuris 1996). Other tactics include placing small-meshed nets, covers, or bags immediately over or around shellfish (Behrens Yamada, unpublished manuscript).

Use of carbaryl as a pesticide

Although potentially a rapid response to an exotic species invasion, the use of pesticides to control green crabs has drawbacks, especially in terms of harming other species in the areas treated. Poisoning has been used in both New England and Canada, however, and, like fencing, it has met with different levels of success (Cohen et al. 1995).

The Washington Department of Fish and Wildlife (2001a) has declared a provisional stance on the use of chemical control at the present time. They report that although chemical methods to control the green crab have been proposed, basic research for implementation is lacking, and any chemical control would have to be "carefully considered" before use. Carbaryl, currently used in selected spots of Willapa Bay for the control of burrowing shrimp, which are known to severely damage oyster populations (Aasen 1997; Campbell and Riener 1992), is a possibility. If implemented, it would first be used in the form of poison bait, initially in a trap, so that effectiveness and damage to other organisms could be studied (Washington Department of Fish and Wildlife 1999d).

Carbaryl is a broad spectrum, synthetic pesticide that belongs to the family of chemicals known as carbamates, which are esters of carbamic acid that inhibit cholinesterase. It is a white crystalline solid that may be formulated as aqueous dispersions, baits, wettable powders, pellets, granules, dusts, suspensions and emulsifiable concentrate solutions (Meister 2000). Carbaryl is mixed with polar organic solvents such as acetone and mixed cresols (Meister 2000), and is applied by ground or aerial spraying methods, at least in the case of burrowing shrimp (Aasen 1997). According to manufacturers, protective clothing should be worn when handling carbaryl, including rubber gloves, respirators, rubber boots (depending on formulation), long-sleeved shirts or jackets, and long pants (Meister 2000). Human health effects may be felt if workers handling carbaryl do not wear protective clothing or are overexposed. Overexposure may cause blurred vision, muscle tremors, difficulty breathing, abdominal cramps, vomiting, diarrhea, weakness, unconsciousness and respiratory failure. Repeated incidents of overexposure could cause severe cholinesterase inhibition, and workers regularly exposed should have periodic checks of red blood cell cholinesterase levels (Information Ventures, Inc. 1995).

Listed as being "toxic to animals of fish diet" and toxic to estuarine and aquatic invertebrates, carbaryl is also extremely toxic to bees (Information Ventures Inc. 1995; Meister 2000). It has been found to be more toxic to crustaceans than to molluscs or fish (Campbell and Riener 1992), but is also moderately toxic to fish and can build up (bioaccumulate) in fish tissue (Information Ventures, Inc. 1995). The Pesticide Action Network (2000) lists this pesticide as being "highly toxic" to both crustaceans and aquatic insects, and "moderately toxic" to fishes, annelids, and zooplankton. Carbaryl is not as toxic to mammals. Its oral LD50 for rats is listed as 246-283 mg/kg (Meister 2000). Carbaryl has signal words of either "Caution" or "Warning" on the label, depending on the formulation (Meister 2000), and this includes the words "extremely toxic to aquatic and estuarine invertebrates" on the Sevin label, carbaryl's most common trade name (personal observation).

Carbaryl is listed as a possible carcinogen by the U.S. EPA, which means there is some evidence of cancer found in animals, but none as yet in human populations (Dickey, personal communication; USEPA 1999). It is also a suspected endocrine disrupter, according to the Preliminary List of Chemicals Associated with Endocrine System Effects in Animals and Humans or In Vitro (Illinois Environmental Protection Agency 1997). This is affirmed by several other lists, according to the Pesticide Action Network (2000). In addition, carbaryl is suspected of being a potential groundwater contaminant (Pesticide Action Network 2000).

Carbaryl does not discriminate against organisms, and may kill many non-targeted species in areas where it is sprayed. These could include Newcomb's littorine snail (*Algamorda subrotundata*), the previously mentioned Washington State Candidate species and Federal Species of Concern (Washington Department of Fish and Wildlife 2000a); the Pinto abalone (*Haliotis kamtschatkana*), also a Washington State Candidate species; and the Dungeness crab, *Cancer magister*, among other sensitive species.

As can be seen, the use of carbaryl against the green crab could pose threats to human health and biodiversity. These issues should definitely be taken into consideration when deciding whether or not to use carbaryl for the control of *Carcinus maenas*.

<u>Bounty programs</u>

Bounty programs, both for green crabs and other species, have been used with varying degrees of success in other regions of the country. They are not currently used in Washington State for green crab control, with one exception. Long-time oyster grower Lee Wiegardt runs his business, Jolly Roger Oysters - Wiegardt Bros., Inc., at Willapa Bay. When green crabs were first discovered in Washington, Mr. Wiegardt instituted a bounty system that paid $5.00 for each green crab brought in. So few crabs were actually found that he eventually gave up on the idea. In fact, only two were actually turned in—green crabs that had been found one-half of a mile off shore in the oyster beds—and the "bounty hunters" didn't even ask for their $5.00. Still, employees of Jolly Roger Oysters are aware of the threat that the green crab imposes on the business, and Mr. Wiegardt believes that some of the employees have taken a few green crabs home and eaten them.

Bay scallops (*Argopecten irradians*) are, unfortunately, a favorite food of green crabs, and some residents along the U.S. east coast have actually instituted bounty programs on green crabs in order to try to decrease their scallop losses in local salt ponds and bays (Fincham 1996; Walton 1997a). In the town of Edgartown, on Martha's Vineyard, Massachusetts, bounty hunters are paid 40 cents a pound for green crabs. These usually end up on a compost pile somewhere. One fisherman, Paul Bagnall, claims that the bounty program is working, saying, "We have removed over 15,000 pounds of green crabs over the last five months from this pond...we have reaped the benefit of this by having a scallop harvest up here this year. It isn't the best the pond has ever seen, but there are certainly plenty of nice healthy scallops to be harvested" (Fincham 1996).

Edgartown destroyed about 22,000 pounds of green crabs trapped out of local salt ponds in 1995 (Walton 1997a). William Walton, who has done a substantial amount of research on green crabs in Martha's Vineyard, reports that the bounty program has alternated with direct trapping by town managers, which is how most towns approach the problem. In his own trapping surveys, he saw no obvious drop in the catch per unit effort for such ponds using this combination of methods, but adds that it wasn't possible to arrange a controlled test of the effect of trapping. Also, the ponds likeliest to be trapped are the ones with the largest green crab populations, so trapping ends up being correlated with "lots of green crabs." He notes, however, that several fishermen have reported to him that they have noticed drops in their green crab catches, enough so that it is not worthwhile to continue to trap the crabs at the set bounty. In other words, if the bounty starts to become effective, the fixed bounty drives the fishermen to stop trapping. His conclusion? "...bounty programs need to actively track the catch per unit effort and increase the benefit as the pest becomes harder to catch" (Walton, personal communication).

There has been some concern that bounty programs have the potential for misuse. Perhaps there have already been instances where individuals have tried to profit from such a program, since large amounts of money can sometimes be made. For instance, a bounty program on the exotic pike minnow, found in the Columbia and Snake Rivers and known to prey upon juvenile salmon, nets some Washington fishermen up to about $40,000 a year (Rogers, personal communication), although there has been no evidence of misuse in that particular program. It is always possible that a green crab bounty program instituted at the present time (when there are very few green crabs in Washington) has the potential of motivating people to bring additional green crabs into Washington. There is also a fear that if the green crab population explodes and a bounty program is instituted afterwards, people may come to depend on the bounty income and actually encourage breeding of green crabs on their private property, or politically obstruct efforts to eliminate bounty programs if they are not working well. Enforcement to ensure that bounty programs are not misused is time-consuming and difficult at best. Yet evidence of misuse of bounty programs appears to be only anecdotal at the present. Two employees at the Nahcotta field station of the Washington Department of Fish and Wildlife indicated that they have not personally ever heard of a situation where a bounty program was misused (Figlar-Barnes, personal communication; Randall, personal communication).

Bounty programs appear to face some interesting limitations. If there are too few organisms around, the program may fail simply due to "lack of interest," as was the case with Wiegardt's program. However, if a species such as the green crab is very abundant, there is always the possibility that the government (or other implementing entity) running the bounty program may have trouble keeping up with the expense of paying bounty hunters. Still, bounty programs may be a viable option in areas with significant numbers of green crabs, though more research needs to be done on the topic. It has been noted that a bounty in Washington at the present time might resolve the problem of aquaculture employees merely smashing green crabs instead of bringing them in to the Department of Fish and Wildlife, and thus provide more data for the research that WDFW is doing (Figlar-Barnes, personal communication).

Fisheries

A related method for possible control of green crabs is the idea of providing a subsidized fishery for them. Lafferty and Kuris (1996) suggest utilizing subsidized fisheries in conjunction with biological control measures, stating "...after all, fisheries are a proven way to eradicate a species." They feel that the green crab, being rather tasty (though too small for traditional commercial seafood markets), might appeal to several ethnic groups, and they cite the example of green crabs being split in two and added to miso soup in Japan (Lafferty and Kuris 1996). Perhaps Lafferty and Kuris are on the right track, as green crabs have not reached pest proportions in Japan. However, a fishery of this sort could obviously only work if there were 1) very large numbers of green crabs and 2) large numbers of people wishing to eat them, and is an idea probably best reserved for areas like San Francisco, and not Washington, at the present time.

Green crabs in Maine recently made news due to a new study that will look at selective harvest as a control strategy. The Beals Island Regional Shellfish Hatchery is investigating the feasibility of harvesting green crabs for specialty markets. It aims to find practical ways for fishermen to identify green crabs, select ones in pre-molting condition, and then market them as a seafood delicacy (Pacific Northwest Marine Invasive Species Team 2000).

In Europe, the green crab is fished commercially, and is used for both food and bait. However, Cohen and Carlton (1995) state that the green crab's small size (relative to other crabs) apparently precludes it from being part of the commercial market in the United States, at least at the present time. Dumbauld (personal communication) adds that selling green crabs as bait would send the wrong message and be very dangerous, but if they *were* to be sold as bait in Washington, one would have to make absolutely sure that they were dead.

Volunteer programs

Organizing volunteers and coordinating their efforts, if done properly, can be a highly efficient way of making the best use of limited resources. Fortunately, the Washington Department of Fish and Wildlife has already been able to enlist dozens of volunteers to assist the agency in its efforts to monitor and control the European green crab. Many more are needed, both now and for future efforts. Currently, about one-third of all green crabs in Willapa Bay and Grays Harbor have been caught by volunteers. In the Puget Sound region, over 67% of the total number of sites over the last three years have been monitored by volunteer groups and individual volunteers (Sato, personal communication; Washington Department of Fish and Wildlife 1999e; Washington Department of Fish and

Wildlife 2001a). At times, volunteers have conducted up to 90% of the Puget Sound monitoring effort (Rogers et al. 2000).

In the summer of 2000, a volunteer program was instituted at Willapa Bay, with fairly good response. Volunteers were composed primarily of property owners on the east side of Long Beach Peninsula (the west side of Willapa Bay). These volunteers monitored traps set out on their properties (typically crayfish traps, in groups of three) and usually checked them daily for the presence of green crabs, from May through September.

Andrea Randall, Washington Department of Fish and Wildlife, Nahcotta, supervised the program, and plans to continue it in future summers. She reports results on the volunteer program for the summer of 2000. After sending out letters to all property owners in the area, Randall received 104 replies giving the Fish and Wildlife Department permission to enter their land in order to set out traps for green crabs. Nine persons wanted nothing to do with the situation. Forty-two persons volunteered to trap. Twelve said they would trap, *plus* Fish and Wildlife personnel could have access to their land. In the end, twenty-three persons actually ended up going through WDFW's training program, and these persons monitored traps on their properties throughout the summer.

For the summer of 2001, 21 of these 23 persons indicated they would trap again. There was no response from the rest of the parties. Randall has high hopes that the agency will be able to increase the number of volunteers at some point, and feels that the response so far has been good (Randall, personal communication).

As discussed in more depth in the "Early detection (monitoring)" section, the Puget Sound region has had a substantial number of volunteers who have been enlisted and trained by the Washington Department of Fish and Wildlife to set crayfish traps and check them for green crabs. Adopt-a-Beach, whose volunteers transferred over to the Puget Sound Restoration Fund when Adopt-a-Beach became defunct, was the first volunteer organization to help in the coordination of trapping efforts in the Puget Sound region. The Washington Department of Fish and Wildlife now contracts with Puget Sound Restoration Fund on this effort, paying $6,000 a season (March - September) to a part-time employee at the Restoration Fund for coordinating the volunteers (Rogers, personal communication). Other traps in the Sound region are checked by local tribes, marine science centers, schools, shellfish growers, and concerned citizens—all of them volunteers. The Washington Department of Fish and Wildlife in Brinnon coordinates these activities.

Organizing volunteers effectively is always a very good option. In Washington State, however, since the catch per unit effort has been declining (Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b; also see **Figure 5**), attempts to organize volunteer efforts may become less fruitful if volunteers feel like they are not making much of a difference. Whether the catch per unit effort is declining because trapping efforts are working, or whether it is declining because recruitment has not been significant, this issue needs to be analyzed.

Public education

In an excellent section of the Summary Report of the Green Crab 2000 Workshop held in Seattle, Sea Grant Oregon (2000) discusses needs and opportunities for educating the public with respect to the European green crab. Currently, west coast educational products on green crabs, either in the works or already developed, include the following:

- identification pamphlets
- fact sheets
- web sites
- specimen display boards
- training workshops
- computer-based presentations
- E-mail list servers
- volunteer monitoring networks
- videos

Suggestions concerning remaining needs included discussion of:

- producing a simple annual one-page update letter to shellfish growers, who have been somewhat overdosed with green crab information and are becoming disinterested since they have not yet been heavily affected by green crabs. The thought was that this might keep the shellfish growers involved without giving them an "overwhelming amount of education."

- educational materials for bait importers, bait shops, and anglers, since green crabs are still imported via the bait market, particularly in California (though this is now illegal in Washington).

• additional educational materials to reduce introductions via home aquaria; the large pet store chain PetSmart has expressed interest in helping to address this problem.

• involving mass media more, such as the newspapers.

• marketing educational products and workshops to non-profit environmental organizations, which have commonly not gotten very involved in aquatic nuisance species issues.

These are just some of the ideas and actions that have already been implemented or proposed. Government entities in the state have been focusing on educational efforts, as well.

The Washington State Aquatic Nuisance Species Committee (1998), in the state's *Aquatic Nuisance Species Management Plan*, has recommended that Puget Sound residents be educated about their role in preventing green crabs and other exotic species from entering marine waters. This includes education on removing organisms from boats and trailers before moving them from one marine area to another (Washington Department of Fish and Wildlife 2001a).

In its most recent *Sport Fishing Rules* pamphlet, which gives seasons, catch limits, and other information to anglers every year, the Washington Department of Fish and Wildlife (2001-02) has a new advertisement: "Please Don't Litter a Critter!!!" (see **Figure 6**). This informative little bulletin, which features a picture of a European green crab, tells citizens what *not* to do when it comes to furthering the spread of endangered species. Every notice such as this

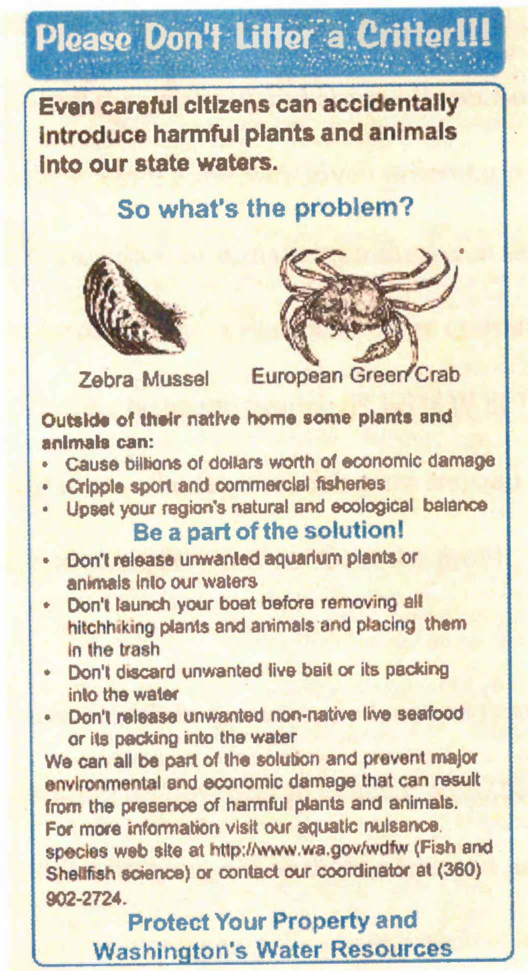

Figure 6. Advertisement alerting public to the problem of introducing non-native species into state waters. (Source: Washington Department of Fish and Wildlife 2001-2002)

one reaches one more person, and further spreads the word about non-native species such as the green crab.

Finally, besides their usual monitoring efforts, the Washington Department of Fish and Wildlife staff in Brinnon expend considerable time and effort toward educating the public in and around Puget Sound. Interested organizations and the general public are given presentations providing background and identification information on the green crab, and most callers or e-mailers with questions are sent a European green crab identification card (Rogers et al. 2000). The Nahcotta branch of WDFW at Willapa Bay also spends time educating the public, schools, shellfish growers, and other interested parties about green crabs, and what they can do about the problem.

As can be seen, much in the way of education is already being done. Additional brainstorming on how best to educate both the general public and specific sectors, and the carrying out of those ideas and plans, are essential if Washington is to win the war against the green crab.

Biological control

Natural predators of the European green crab include fishes, gulls, and other crabs; these predators keep the green crab in check in its native range. The green crab is also vulnerable to certain parasites and egg predators. It is the latter that offer the greatest hope of success in controlling non-native green crabs by using biological control methods, according to Behrens Yamada (unpublished manuscript). At the First International Workshop on the Demography, Impacts and Management of Introduced Populations of the European crab, *Carcinus maenas*, which was held in Tasmania in March of 1997, biological control was one of two options suggested that were likely to be effective, out of the many possibilities for green crab control (Thresher 1997). However, in many regions, including the U.S. west coast, biological control using parasites and egg predators is only in the preliminary stages of exploration. This section reviews current biocontrol research and findings, with the hope of providing a convenient summary and provoking thought about future options.

Hoeg, Glenner, and Werner (1997) have studied the parasitic isopod *Portunion moenadis* for use as a biological control agent on the green crab. They observed a 2% predation rate on green crabs in a study done on the west coast of Sweden, where the green crab is native. *Portunion maenadis* essentially feminizes and castrates the host crab (Behrens Yamada, unpublished manuscript); the mode of this transformation is thought to be hormonal (Rasmussen 1973, as cited by Behrens Yamada, unpublished manuscript). Too many details remain unknown about *Portunion maenadis* at the present time to justify using it in any field trials as a biological control agent (Hoeg, Glenner, and Werner 1997).

The parasitic barnacle, *Sacculina carcini*, is also known to infect green crabs, robbing its host of nutrients, retarding molting, and castrating the crab, regardless of sex. During a later state of infection, an external sac at the base of the crab's abdomen is formed, to which the male *Sacculina carcini* larva attaches itself (Behrens Yamada, unpublished manuscript). This sac contains the gonads of the parasite, though it may resemble an egg mass, which causes both male and female green crabs to exhibit brooding behavior such as cleaning, aerating and protecting the sac. Larvae of the parasite may later be released (Crothers 1968, as cited by Behrens Yamada, unpublished manuscript). The sac remains attached to the crab for up to 6 months, after which the crab often dies (Rasmussen 1973, as cited by Behrens Yamada, unpublished manuscript). Back in western Sweden, Hoeg, Werner and Glenner (1997) discovered that one locality along the coast showed 29.5% of green crabs infected with *Sacculina carcini*, and another locality showed a 17.4% infection rate. They conclude that, if *Sacculina carcini* was introduced in Australia, it would most likely infest green crab populations, but add that further experimentation should be done first. Additionally, Minchin (1997) investigated the influence of this parasite upon the green crab within its home range. Though he found that green crabs were parasitized by *Sacculina carcini* in all studies performed in Irish waters, Minchin feels that the potential benefits of introducing this parasite to control invasive green crab populations are small. Murphy and Goggin (2000) have done a recent study on the genetic discrimination of sacculinid parasites and have noted the implications for control of green crabs. Their data suggest that *Sacculina carcini* "...infests at least two genera of crabs from a broad geographic distribution" and therefore may limit its biological control prospects. In Australia, where *Carcinus maenas* is an invasive species, Hoeg, Werner, and Glenner (1997) exposed green and other crabs to this parasite in the laboratory. *Carcinus maenas* developed infections after exposure, but fortunately, the native *Paragrapsus gaimardii* did not. However, it is not known at this time whether *Sacculina carcini* could negatively affect Dungeness and other native crabs on the U.S. west coast. In addition, although this parasite heavily affects some green crab populations, others are left untouched (Behrens Yamada, unpublished manuscript). Interestingly, Lafferty and Kuris (1996) indicate that this parasite seems like the best candidate for biological control of the green crab; they state it is highly host-specific and that present information suggests it would be a safe control agent. But they do also stress the need for carefully controlled experiments that could determine what effects, if any, *Sacculina carcini* would have on native crab populations.

Two types of egg predators also offer hope in the area of biological control. The first of these are the nicothoid copepods, small crustaceans that complete their development as symbionts of crabs. Adult female nicothoid copepods (*Choniosphaera cancrorum*) resemble green crab eggs; they live in, and move around freely within, the green crab's egg mass. Eventually they suck out the contents of the crab eggs. The nicothoid copepods' egg packets also attach to green crab eggs, and nicothoid larval stages live within the egg masses of the green crab (Behrens Yamada, unpublished manuscript; Johnson 1957, as cited by Behrens Yamada, unpublished manuscript).

The nemertean worms *Carcinonemertes carcinophilia* and *C. epialti* may be useful in the control of green crab populations. These thin, elastic, non-segmented worms (Behrens Yamada, unpublished manuscript) are also egg predators. An attractive feature of *Carcinonemertes epialti* as a potential biological control agent is that this particular species is already native to the U.S. west coast. Torchin et al. (1996) have studied the infestation of green crabs by *Carcinonemertes epialti*, and they report that it has already infected the green crab population in Bodega Harbor, California. They feel that it could potentially restrict the green crab's numbers. However, Lafferty and Kuris (1996) feel that it is unlikely that this nemertean alone will affect green crab populations, since the infestation rate is rather low. Other U.S. west coast crabs known to harbor *Carcinonemertes epialti* include *Hemigrapsus oregonensis* (yellow shore crab, or hairy Oregon shore crab), *H. nudus* (purple shore crab) and *Pugettia producta* (kelp crab) (Behrens Yamada, unpublished manuscript). The other nemertean worm species, *Carcinonemertes carcinophilia*, has been found by MacGinitie and MacGinitie (1968, as cited by Behrens Yamada, unpublished manuscript) to parasitize the green crab in Europe. However, it had apparently not been found to parasitize any green crab populations on the east coast of North America at the time of that report. Kuris (1997) has also studied nemertean egg predators and made assessments of their use as potential biocontrol agents for the green crab. He states that it seems "...likely that host specificity of *C. carcinophilia* is greater than indicated by its current usage," but stresses that there are no direct studies of its impact as an egg predator, and that additional research very much needs to be done (Kuris 1997).

Additionally, Goggin (1997) looked at other parasites, excluding *Sacculina carcini*, that could regulate populations of the green crab. After studying various viruses, dinoflagellates, ciliates, and nemerteans, she came to the conclusion that of those she studied, ciliates actually had the "best potential" for biological control of green crabs. However, as seems to be the usual case with potential biological control agents, she noted that extensive experimentation would have to be performed, especially in order to discover whether native crab populations could be threatened by the ciliates.

Behrens Yamada has also addressed the possibility of enhancing the habitat for a native natural enemy—another approach to biological control:

> On the West Coast of North America it may be possible to increase the abundance of native shore crabs in the high intertidal zone of mudflats where green crab larvae settle out from the plankton. This could be accomplished by adding shelters such as rocks, stepping stones, plywood sheets and oyster shells. Both shore crabs *Hemigrapsus oregonensis* and *H. nudus* have been shown to colonize such newly created shelters (Visser 1997, Ison 1998). Larger crabs typically displace smaller crabs from shelters and often prey on them, regardless of species...Jensen et al. (2000) showed that the shore crab *H. oregonensis* is a better competitor for shelter than green crabs of similar size. It is thus conceivable that adding shelter could give the native shore crabs a competitive advantage over green crabs of smaller or equal size. Predation of green crab recruits by the two *Hemigrapsus* species could also occur. The outcome of such shelter addition on green crab

abundance would need to be investigated (Behrens Yamada, unpublished manuscript).

Although it is clear that different forms of biological control may hold promise for the suppression of green crabs, it is also apparent that much more research is needed in this area. Since time is of the essence in many current scenarios involving *Carcinus maenas* invasions, methods other than biological control must be implemented while essential funding for further research on biological control is pursued.

Genetic alteration

Little has been done in the way of research in this field, although there are now a number of different molecular approaches for control and possible eradication of pest species such as the green crab. These include ploidy/chromosome manipulation, controlling the sex composition of populations (via hormonal treatments and transgenic manipulation), immunocontraception, and the introduction of inducible fatality genes via transgenic techniques (Grewe 1997). According to Grewe (1996, as cited by Grewe 1997), only the inducible fatality gene "offers any real prospect of long-term control or even eradication" of species like exotic carp, which Grewe has studied the most. He feels that these concepts are "quite general and could be applied to other pest species," and states reasons for considering the inducible fatality gene as being related to its long-term application and its potential for 100% security (Grewe 1996, as cited by Grewe

1997; Grewe 1997). Thresher (1997) states that participants in the Australian international workshop on green crabs of 1997 felt that approaches such as this had considerable merit and were worth pursuing, although most noted they lacked expertise in the area.

Can we predict future recruitment?

Green crabs were first observed in the State of Washington in the summer of 1998. It is currently believed that the mode of travel was "most likely a matter of simple larval transport" (Dumbauld, personal communication). Ocean currents flowing north from California, the original source of the west coast green crab population, were thought to have been especially favorable for facilitating transport of the crab larvae in the winter of 1997-98. Green crab ages were remarkably similar when they turned up at sites in Oregon, Washington, and British Columbia in 1998, indicating that they were probably all swept northward in the same few-month period (Dumbauld, personal communication).

The 1998 larval recruitment was almost certainly related to the El Niño event of the winter of 1997-98, more specifically, the months between September 1997 and April 1998. Although the El Niño ocean conditions that year were somewhat anomalous and extremely favorable for larval transport (Behrens Yamada et al. 2000), range expansions of marine invertebrates and fish are common observances during and after an El Niño event (Schoener and Fluharty 1985, as cited by Behrens Yamada et al. 2000).

We can predict that a large-scale recruitment event like the one that happened in 1998 will happen again. We can't always say exactly when, although some scientists are now saying they have enough evidence to predict an El Niño in the coming winter of 2001-2002 (Schmid 2001). Behrens Yamada et al. (2000) forecast that the green crab will increase in abundance in both Oregon and Washington, and that it will expand its range through dispersal of its larvae in this manner.

A word on government incentives

When discussing the issue of how green crabs affect natural biodiversity (see "Additional impacts upon biodiversity in Washington State" in this paper), particularly with respect to "priority" species, it should be noted that the Endangered Species Act does not require landowners to maintain or restore habitats for listed species, let alone species of potential concern (Wilcove et al. 1998). (These species of potential concern include categories such as Washington's State Candidate species—the Olympia oyster, Pinto abalone, and Newcomb's littorine snail, among them.) Thus, for many private landowners, including a company such as Weyerhaeuser that owns significant amounts of property bordering Willapa Bay, there is no obligation to control for exotic species such as the green crab. Nor is there much incentive, as the cost of managing for invasive species can be considerable. At present, these costs are usually not tax-deductible (Wilcove et al. 1998). Since the U.S. Fish and Wildlife

Service has less money to spend per species as the list of threatened animals and plants steadily grows, it may become imperative to supplement the regulatory controls of the ESA and other laws to provide incentives for landowners who manage their property to benefit species in peril or species of potential concern (Wilcove et al. 1996).

If no species of concern or potential concern exist on a property owner's land, that does not diminish the threat of invasive species to the overall environment or to commercial enterprises such as aquaculture. Perhaps incentives, via tax breaks, could be offered to individuals or companies who work with entities such as the Washington Department of Fish and Wildlife to manage for invasive species along their shorelines. Implementation of such incentives would be most easily accomplished by enacting legislation on a statewide level. Since Washington State has no state income tax, perhaps such tax breaks could come from the local property tax infrastructure.

CURRENT STATUS OF WASHINGTON STATE'S GREEN CRAB POPULATION AND RESPONSE

Population status

Figure 4 (found on page 46) shows the locations where the Washington Department of Fish and Wildlife has placed green crab traps in Willapa Bay and Grays Harbor. The figure shows sites where green crabs have, or have not, been captured to date. In Willapa Bay, 50 of the 73 survey sites have resulted in green crab captures; in Grays Harbor, exactly half (27) of the survey sites have netted one or more green crabs.

The majority of WDFW's coastal trap checking is done from April through September. Monthly monitoring is done at three locations in Willapa Bay and two locations in Grays Harbor. In August and September, large baywide surveys are conducted at over 20 sites in the bays. Similar surveys continue to be performed during other months of the year. Most traps are "rotated" into different sites in order to provide a more comprehensive picture of green crab distribution, although some remain in the same spots as controls. Thus, sites (exclusive of monthly sites) end up being checked an average of 3-5 times during the summer months. Volunteer property-owners and others are encouraged to check their traps as often as possible and strive for once every 24 hours (Dumbauld, personal communication; Rogers et al. 2000).

The large majority of green crabs captured in Willapa Bay and Grays Harbor have been found in the intertidal areas from April to October each year. Most of these, by far, have been in the low saltmarsh and either in *Spartina* habitat (the introduced cordgrass) or in *Triglochin* (native arrowgrass) and *Scirpus* (American threesquare) territory (Rogers et al. 2000). At the present time, green crabs tend to be found more in higher salinity areas near the mouth of Willapa Bay, such as the eastern side of Long Beach peninsula (which is the west side of the Bay), or in the more northern half of the bay. This is probably not due to salinity factors, but to the fact that these locations are near the mouth of the estuary (Dumbauld, personal communication; also see **Figure 4**).

In the winter (late October to March), green crabs can no longer be found in the intertidal areas of Washington bays, but have moved into deeper subtidal waters. The reason for this seasonal movement is not entirely clear, but it may have to do with retreat by the crabs to areas of higher temperature and salinity (Rogers et al. 2000). Any crabs captured in these winter months are usually found in shell bags or via dredging activities by oyster growers, although the majority of green crabs that growers turn in are found in the spring in oyster seed bags (Dumbauld, personal communication; Rogers et al. 2000).

The Washington Department of Fish and Wildlife's field station in Nahcotta keeps detailed records of their trap-hours, and the number of green crabs captured in these traps. Their catch per unit effort has fallen substantially from

1998 to the year 2000, which is good news (see **Figure 5** on page 47; note 2001 CPUE figures are not yet available). In 1998, WDFW's CPUE was 0.015 crabs per trap-hour in Willapa Bay (197 crabs divided by 13,374 hours); in 1999, CPUE in Willapa Bay was 0.003 (264 crabs divided by 93,327 hours), and in 2000, CPUE was 0.002 (101 crabs divided by 63,288 hours). For Grays Harbor, CPUE has been approximately even at 0.001 crabs per trap-hour for the years 1999 (29 crabs divided by 24,648 hours) and 2000 (21 crabs divided by 15,240 hours). Trap-hour data for 1998 are not available for Grays Harbor (Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b).

Table 2 breaks down the numbers and sexes (including ovigerous females) of green crabs found in both Willapa Bay and Grays Harbor from the years 1998 through 2000. These numbers represent *all* green crabs caught in the bays, not only by WDFW, but also by local oyster growers, landowners, students, and the Shoalwater tribe. **Table 2** also notes the size range of the crabs during those years. As one can see by the table, there has not been as much of a decrease in crabs caught in Grays Harbor (39% from the peak year 1999 to the year 2000) as there has been in Willapa Bay (a 58% decrease from the peak year 1999 to the year 2000) (Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b). This difference between the two locations may be a reflection of trapping efforts paying off more in Willapa Bay, where the Department of Fish and Wildlife is able to expend

	Willapa Bay					Grays Harbor				
Year	Males	Females	Unsexed	Size Range (mm)	**Total**	Males	Females	Unsexed	Size Range (mm)	**Total**
1998	203	100	1	25.7 – 66.0	304	21	8	1	25.3 – 58.3	30
1999	239	103 3 w/eggs	5	30.3 – 76.8	347	108	15 2 w/eggs	1	27.7 – 78.0	124
2000	104	41 2 w/eggs	0	19.3 – 90.0	145	63	13 1 w/eggs	0	32.7 – 82.1	76
All years	546	244	6		**796**	192	36	2		**230**
% decline from 1999 – 2000					**58% decline from 1999 - 2000**					**39% decline from 1999 - 2000**

Table 2. Numbers and genders of green crabs caught in Willapa Bay and Grays Harbor, Washington, from 1998 to 2000. (Source of data: Washington Department of Fish and Wildlife 1998-2000a; Washington Department of Fish and Wildlife 1998-2000b)

more of its time and energy. If that is true, it would also follow that green crab populations are not going down "naturally" simply due to a lack of recruitment.

In fact, (see **Figure 7** and **Figure 8**), data indicate that small crabs of a new year class have appeared in both 2000 and 2001 (the figures exhibit data from the years 1998-2000). This indicates that either further recruitment has occurred in both bays, or that crabs in both bays are reproducing. Analyzing the 2001 trapping effort results will be important in learning whether a self-sustaining population has been established in Willapa Bay and Grays Harbor (Washington Department of Fish and Wildlife 2001a). As of June 2001, the same numbers of crabs have been found so far this year (2001) as in the year 2000 (Figlar-Barnes, personal communication) instead of going down, as they have in previous years.

So, the good news: trapping is working. The "bad" news? The Washington Department of Fish and Wildlife probably won't know until later in the year (2001) how well that trapping has worked, and whether it will have been enough to keep self-sustaining green crab populations from becoming established.

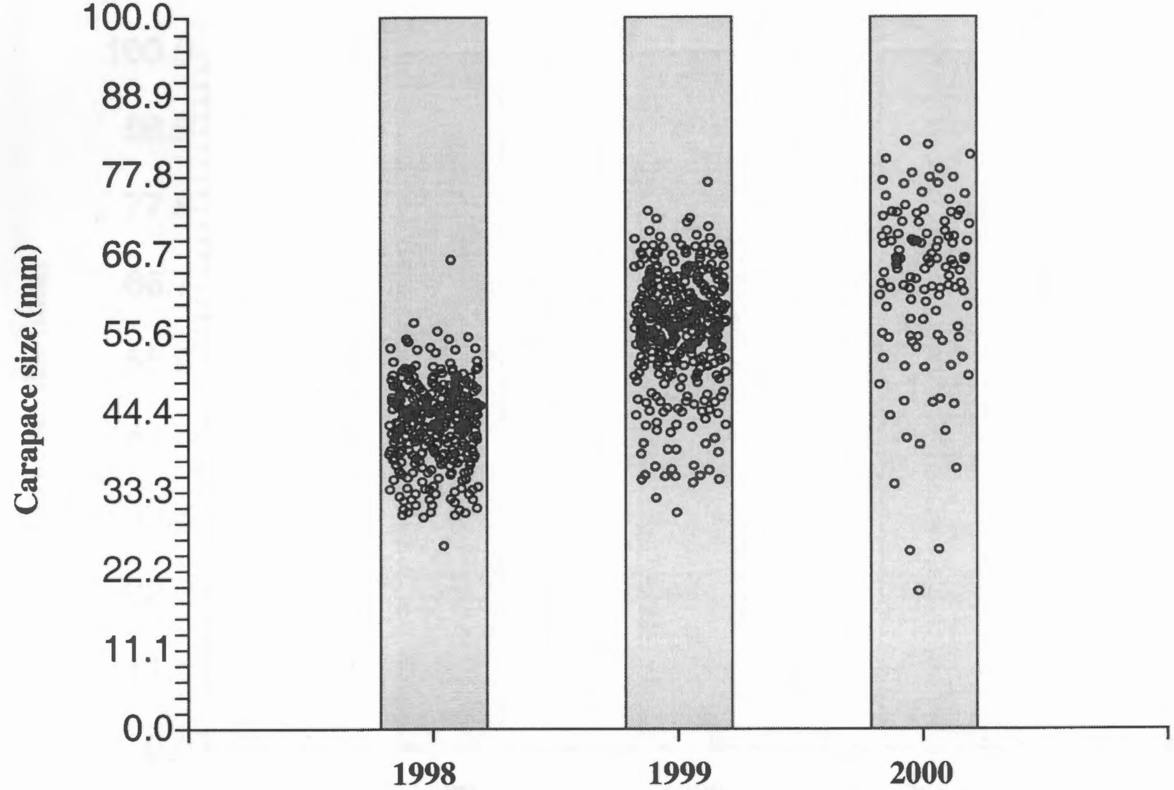

Figure 7. Sizes of green crabs found in Willapa Bay, Washington, for years 1998 – 2000. Each small circle represents one crab. (Original chart: Figlar-Barnes and Randall 2001)

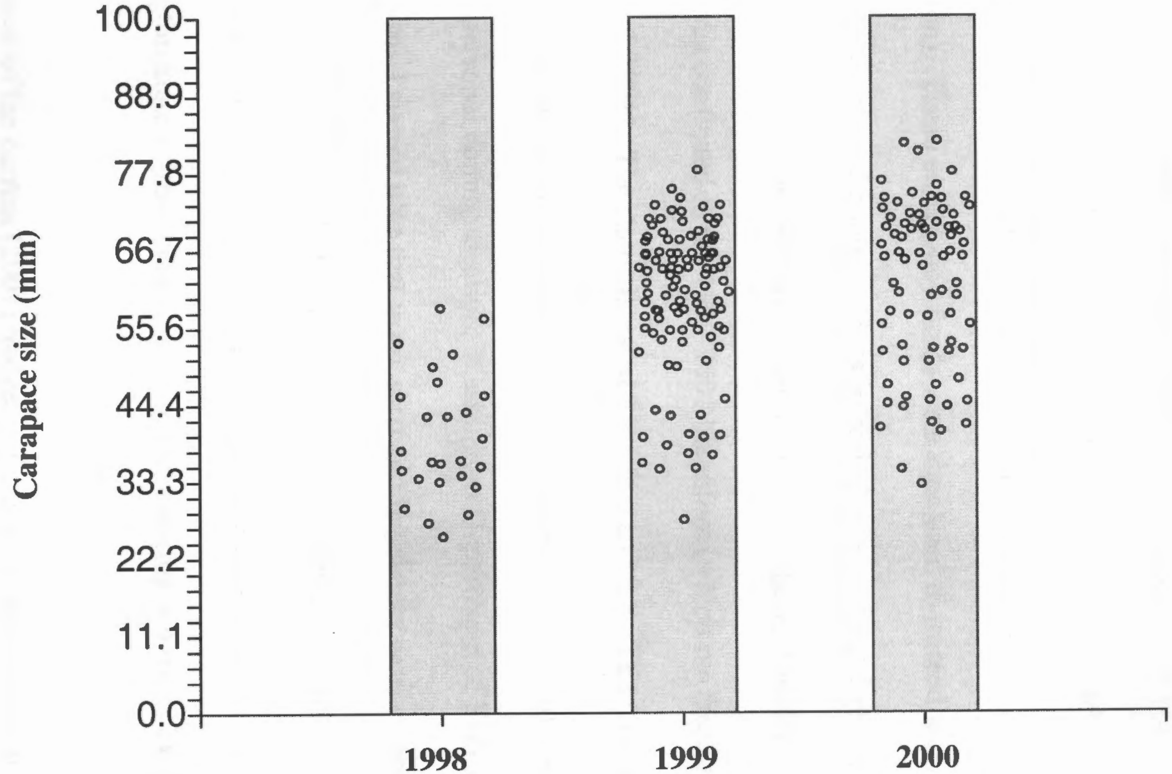

Figure 8. Sizes of green crabs found in Grays Harbor, Washington, for years 1998 – 2000. Each small circle represents one crab. **(Original chart: Figlar-Barnes and Randall 2001)**

Funding for green crab programs

In 1998, the year the European green crab was discovered in Washington's waters, Governor Gary Locke provided $110,000 in emergency funds for the fiscal year 1999 (which ended in June of 1999). Employees at the Washington Department of Fish and Wildlife began searching for crabs and collecting them even before the emergency funds were provided (Dumbauld, personal communication). These emergency funds were then used to immediately begin large-scale monitoring and control efforts in both the Puget Sound region and on Washington's coast. Fortunately, the effort did not stop there. Funding for green crab control was continued in the 1999-2001 biennium (which ran from July 1999 through June of 2001). The state allocated $464,000 and 3.5 FTEs (full-time employees) for the biennium; $40,000 of this amount was for one-time start-up costs (Olsen, personal communication; Washington Department of Fish and Wildlife 1999b). I should note that many staff and legislators worked hard to see this funding implemented, but State Senator Ken Jacobsen has perhaps been this effort's greatest champion. It is due to the far-sightedness of Jacobsen and others that Washington State's green crab control and monitoring programs exist today.

Because of the current (2001) budget deficits in Washington State, Governor Gary Locke imposed a mandate at the beginning of the year 2001 that all agencies, across the board, cut their budgets. There were worries in early 2001 that funding for the green crab program would be reduced or eliminated. After all, the present allocation is a fairly large sum of money and, in addition, there may be the perception that green crabs are not of immediate concern; they have done no damage that the government or the public can discern at the present time.

The over $400,000 that has been allocated to Washington State's green crab programs comes from the state's general fund (state appropriation), with the Washington Department of Fish and Wildlife as the implementing entity. For now, the general fund continues to supply this appropriation. Approximately half of the amount is used for the Puget Sound region, and the other half for Willapa Bay and Grays Harbor (Smith, personal communication). Funding for the green crab program is provisional, and is directed specifically at green crabs (Rogers, personal communication). The state general fund is, by far, the major source of the green crab program's funding. The Washington Department of Wildlife does receive small amounts of funding from other sources, generally not more than a few thousand dollars annually, specifically for green crab monitoring and control. For instance, the National Invasive Species Act (NISA), through the implementing entity of the U.S. Fish and Wildlife Service, provides the Aquatic Nuisance Species Division of WDFW with some funding, but only an estimated $3,000 annually goes toward the green crab programs (Smith, personal communication).

Fortunately for the green crab programs, it appears that the 2001-2003 biennium will see the state's general funding stay in place, minus the original $40,000 one-time start-up costs (Olsen, personal communication). This means that the state will be providing a total of $424,000 for the upcoming two-year period.

CONCLUSIONS: LESSONS FROM WASHINGTON STATE'S EXPERIENCE

Upon their discovery that nearly half of imperiled species in the United States are threatened by alien species, and recognizing that numbers of alien species are steadily growing, Wilcove et al. (1998) have made the statement that "...this particular threat may be far more serious than many people have heretofore believed." Any lack of continued attention to this threat in Washington may determine whether the European green crab does indeed thoroughly invade our ecosystems. I believe that if we do not continue to address the problem, it will.

Given the circumstances, especially budget constraints, the State of Washington has responded admirably to the threat of a green crab invasion. Time will tell how well these efforts have paid off, but it appears at the present that the state has made good decisions and choices in its handling of the situation. Up to this point in time, the Washington green crab plan can be seen as a good model for other states to follow when dealing with threats of marine invasions and/or invasions in early stages.

The state has also made efficient use of resources by combining efforts addressing more than one invasive species. This ultimately has resulted in the passage of legislation that not only deals with green crabs, but also with other invasive species such as the Zebra mussel (for examples of this legislation, see the

"Prevention measures" section earlier in this paper). In fact, the state combined efforts to focus on Zebra mussels and green crabs by forming the Zebra Mussel and European Green Crab Task Force, which first met on September 17, 1998, and which approved a final report and recommendations on November 20, 1998. This task force consisted of 86 members and was organized into two committees (the Zebra Mussel Committee and the Green Crab Committee) and four sub-committees. The two committees provided education resources and assisted each sub-committee in developing recommendations and a final report. The four sub-committees were established to address each major pathway of potential introduction of invasive species—aquatic plant and animal suppliers, ballast water, aquaculture and live seafood industry, and recreational boating. Recommendations were developed for each of these areas, and subsequent legislation showed that the Task Force's efforts had been taken seriously. The Task Force also ended up recommending as high priority (among other things) that green crab monitoring and control programs be continued and expanded, and estimated a biennium funding level of $464,788, which the state granted during the following legislative session (Washington Department of Fish and Wildlife 1999c).

Even before the arrival of the green crab in Washington, government and private entities were working on developing the *Aquatic Nuisance Species Management Plan*, a comprehensive management strategy to address important aquatic nuisance species issues (Washington Department of Fish and Wildlife significantly correlated with increasing abundances of green crabs in Bodega Bay, California (Grosholz 1997). The Washington Department of Fish and Wildlife (2001a) states that nearly three dozen mussels under 45 mm in length may be eaten daily by one green crab, and Wilhelm (2000) reports that a green crab can eat more than 40 young shellfish per day. Regarding the Dungeness crab fishery, the McDonald et al. (2001) laboratory trials showed green crabs consistently out-competing equally-sized Dungeness crabs for food and shelter sources; Cohen et al. (1995) and Grosholz and Ruiz (1995) report that the Dungeness crab can be consumed by green crabs at up to the green crab's own size. Given all these figures, it is very much within the scope of reason that a large-scale green crab invasion could affect 20% of existing fisheries and shellfish industries within the State of Washington. This, therefore, amounts to annual state losses of approximately $24 million (the estimate of dollars lost does not, of course, include the hard-to-define costs of loss of biodiversity and damage to non-commercial species).

Given the scarcity of monetary resources available in Washington State, are we relegating an appropriate amount of money toward green crab detection and control? I certainly believe so—$424,000 seems well spent when examining a potential scenario of $24 million in annual loss to state industry. Are we utilizing the best current detection methods in the Puget Sound region and the best current control methods in the Willapa Bay and Grays Harbor areas? I feel that we are. But I also believe that these need to be expanded.

RECOMMENDATIONS

More funds need to be allocated overall to the green crab program in Washington State. The Washington Department of Fish and Wildlife has done, and is doing, a fantastic job of green crab monitoring and control statewide with a current budget of not much more than $424,000. In order to ensure that the groundwork they have laid and the research they have done does not go to waste, these efforts need to be expanded, as noted in the following paragraphs. **Table 3** summarizes these recommendations for green crab control and monitoring efforts in the future.

Specifically, additional funding should be used toward increasing the number of monitoring sites in the Puget Sound region, to include new sites monitored by WDFW, and—especially—additional sites to be checked by volunteers. Organizing volunteers and coordinating their efforts is one of the very best ways to make the best use of limited resources. It seems wasteful *not* to allocate additional funds for the purposes of coordinating volunteer efforts. Recall that the Puget Sound WDFW contracted last season (March - September 2000) with the Puget Sound Restoration Fund to hire a part-time coordinator responsible for organizing and monitoring volunteers. Last year (2000), this resulted in 37 additional monitoring locations being checked around the region—roughly one-fifth of all locations in the Puget Sound area—all for the relatively small price of $6,000! Adding $12,000-$18,000 to the Puget Sound region's biennial budget in order to pay 2 to 3 more non-profit organization coordinators to monitor networks of volunteers could result in an additional 70 to 105 traps being monitored. This increase in the number of monitoring sites is essential in order to ensure that any green crabs are detected as early as possible. It is fortunate that the Washington Department of Fish and Wildlife has already been able to enlist dozens of volunteers to assist with efforts to both monitor and control the European green crab. Many more are needed in the future—but with well-organized volunteer programs, Washington State will get more than it pays for.

Having trouble coming up with volunteers or volunteer organizations? Why not expand the list of groups under consideration? For instance, there are several hunting and fishing organizations and clubs that may be amenable to volunteering to check traps. Such groups are usually quite conservation-minded, and also may perceive that they will reap the benefits of heading off a green crab invasion—especially avid clammers, crabbers, and the like.

It is extremely important that more attention be given to Grays Harbor, where WDFW does not currently have the time or the funds to set up and coordinate an extensive trapping network. Trapping efforts, it appears, do work (see the "Population status" section) and so, obviously, we should be doing more trapping. At least one additional full-time position is warranted in order to adequately cover program needs in Grays Harbor. Grays Harbor has as much potential for a green crab explosion as Willapa Bay, but limited resources and time have resulted in WDFW focusing far more of their efforts on Willapa Bay, where their field station is located.

And what about the possibility of another large recruitment event? It almost certainly will happen. Additionally, the population explosion and range expansion of the green crab on the U.S. east coast has been correlated with a rise in ocean temperatures around the turn of the twentieth century (Rogers 2001a). If this same trend holds true on the U.S. west coast, the green crab problem can only be exacerbated by predicted climate changes. State governments are not normally in the habit of preparing for disasters that are not somewhat imminent (and with limited budgets, who can blame them?). But the state needs to be mindful that it may suddenly need to come up with additional funding in the event of another recruitment incident, and a certain level of preparedness is warranted. This may include strategies such as devising a good emergency response plan ahead of time or being ready to quickly install additional personnel in sites such as Grays Harbor. Of course, one of the best ways to be prepared is to have the "pre-recruitment event" situation firmly under control. This is why it is imperative that we step up Puget Sound monitoring efforts and Grays Harbor trapping practices as soon as possible.

And where do these additional funds come from? Although I would make the argument that one more full-time employee in Grays Harbor, and 2 or 3 more allocations of $6,000 (to be used for contracting with volunteer organizations to coordinate trap checking), does not equal a large sum of money, it does need to come from somewhere. If the state cannot provide this additional insurance money on its own, perhaps a tax could be placed upon the persons who reap the benefits of beautiful shorelines and trouble-free waters. Adding a small tax to, say, a State of Washington Recreational License could bring in additional revenue. A growing number of people seem to be aware of the potential problems associated with exotic invasions; they might be quite amenable to a "nuisance species prevention tax." Hunters and fishermen in particular, as I have already mentioned, are often quite conservation-minded, and may be willing to bear this small added expense.

Public education can be inexpensive, and sometimes it can be free. Enlisting the media's help in drawing attention to the green crab problem may be one way of educating the public, not only on identification of green crabs, but on the dangers of toting them around. Increased attention should also be given to addressing education in specific sectors of the public. Ideas such as the ones found in the "Public education" section in this paper are invaluable, and more workshops addressing these outreach and education issues may generate even more ideas and spur further action.

What is the scientist's role in addressing these issues? A good start would be to turn more attention to biological control research. As Lafferty and Kuris (1996) state, "The absence of studies on the control of introduced marine and estuarine pests approaches fatalism." They feel it is odd that there has been so little response to exotic invasions by researchers and management agencies, given that biological control has such a long track record of remarkable successes in agriculture, and since the field has been so well established and analyzed.

Last, scientific research and facts relating to the impact of green crabs on non-commercial, and sometimes threatened, species now also need to be added to the arguments for controlling *Carcinus maenas* and other invasive species. We cannot afford to overlook these important issues of biodiversity, and their added weight may help tip the scales toward retention of, and increases in, crucial funding for control of exotic species.

The real question is not *whether* we should address a green crab invasion, but how, and how fast. One option not mentioned in the control section of this paper is the option of doing nothing at all. There is a train of thought that believes that humans should succumb to the inevitability of exotic species invasions, and sit back and watch our existing "natural" environments morph into different ones. Not only are out-of-control exotic invasions not inevitable, I believe that most persons—from shellfish growers, to ecologists, to concerned citizens—do not wish to see "different" environments that have been altered by invasive species. We like what we have! And if this is so, our elected officials and policy makers must listen. If they do not, it *is* inevitable that *Carcinus maenas* will infest the waters of Washington State, and it will only be a matter of when. Our current green crab prevention, detection, and control programs are comparable to a homeowner who pays annually for flood insurance when living in a flood plain. The homeowner knows that the floods will come. The homeowner also knows that the floods may not come in his or her lifetime, but nonetheless does not risk suffering the loss. Washington State's scenario is nearly the same, with one exception: green crabs are only around the bend of the next river. Economic and environmental disaster flow in their wake, and we owe it to ourselves to pay the insurance premiums before we no longer have a choice in the matter—and in doing so, we may very well provide our neighbors with a good example, too.

1) Increase number of monitoring sites in the Puget Sound region—specifically, increase sites that can be monitored by volunteers by 70-105 sites
2) Achieve goal 1) by adding $12,000-$18,000 to Puget Sound region biennial budget in order to pay 2 to 3 more non-profit organization coordinators (at $6,000 apiece) to monitor networks of volunteers
3) Increase efforts made to enlist and coordinate volunteers utilizing expanded list of volunteer and not-for-profit organizations, such as hunting and fishing groups
4) Increase staff in Grays Harbor by at least one full-time position in order to expand and concentrate on additional trapping and monitoring sites
5) Prepare emergency response plan in event of sudden influx of green crabs; this is of particular importance if another El Niño is predicted
6) Explore the possibility of a "Nuisance Species Prevention Tax," to come from sources such as State of Washington Recreational Licenses, as a source for additional funding for green crab programs
7) Investigate cost-effective ways to increase public education, which may include enlisting the help of media sources
8) Fund at least one position for long-term study investigating past, present and possibly future methods of biological control
9) Scientists should continue to research existing impacts of green crabs on aquaculture and fisheries, particularly in field experiments (primarily in places such as California, where green crabs are already abundant and can be studied readily)
10) Take into consideration potential impacts of green crabs on non-commercial species of concern, such as threatened/sensitive species listed in **Table 1**

Table 3. Recommendations for future green crab control and monitoring efforts in Washington State.

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