

**Ecological and Economic Impacts and Invasion Management
Strategies for the European Green Crab**

Developed for:

**National Center of Environmental Economics
U.S. Environmental Protection Agency**

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June 3, 2008

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Acronyms

AIS	Aquatic invasive species
CPUE	Catch per unit effort
EDA	Estuarine Drainage Area
ELMR	Estuarine Living Marine Resources
GARP	Genetic Algorithm for Rule-set Prediction
NCPDI	National Coastal Pollutant Discharge Inventory
NOAA	National Oceanic and Atmospheric Administration
USGS	United States Geological Survey
WDFW	Washington Department of Fish and Wildlife
WTA	Willingness to accept
WTP	Willingness to pay
YOY	Young-of-year

1. Introduction

Aquatic invasive species (AIS) are organisms introduced to marine or freshwater ecosystems to which they are not native and whose introduction causes harm to human health, the environment, or the economy. The numbers of AIS entering the United States appear to be increasing largely as a result of increased global trade and travel. Estimating the ecological and economic impacts of AIS is very difficult, and consequently, the economic impacts of AIS have been estimated for only a limited number of species in specific geographic locations. Comprehensive national and regional estimates of impacts are lacking for most AIS (Lovell, Fernandez, and Stone, 2006). Estimates of the total economic impact of all invasive species, both terrestrial and aquatic, in the United States are incomplete in terms of both species covered and impacts addressed. These estimates vary widely from \$97 billion (1996 dollars) for 79 exotic species during the period from 1906 to 1991 (U.S. OTA, 1993) to \$120 billion per year (1996 dollars) (Pimentel et al., 2005).

Knowledge of the magnitude and the temporal and spatial scale of AIS impacts relative to other environmental concerns in the United States is needed to determine if intervention is required and if so, to help design and implement cost-effective management options. The National Oceanic and Atmospheric Administration (NOAA) and the U.S. Fish and Wildlife Service jointly administer, with the participation of U.S. EPA and other agencies, the Federal Aquatic Nuisance Species Task Force. This program was established by the National Invasive Species Act and the National Invasive Species Management Plan (Executive Order 13112), which calls for identifying invasive species and their potential ecologic and economic impacts. One of the recommendations of a 2005 EPA-sponsored workshop on the economic impacts of AIS was to develop more comprehensive estimates of impacts by assessing impacts on a larger geographic scale and by including all types of potential impacts, not just the costs of management, prevention, and eradication. In partnership with NOAA, EPA initiated development of a methodology for linking ecological models with economic models for use in future analyses of AIS impacts. EPA applied the methodology to this case study of European green crab impacts.

The goals of this case study are to estimate the European green crab's current and historical impacts on ecosystem services on the East Coast of the United States and to estimate the European green crab's current and potential future impacts on ecosystem services on the West Coast of the United States under various invasion scenarios.

The European green crab (*Carcinus maenas*) is a relatively small eurythermic and euryhaline crustacean, capable of surviving in a broad range of temperatures and salinities. A successful aquatic invader native to Northern Europe, this crab has established populations in North America, South Africa, Japan, Argentina, and Australia (Green Crab Control Committee, 2002). Green crabs were first discovered on the East Coast of the United States in 1817, but did not appear on the West Coast until 1989, when they were discovered in San Francisco Bay (Cohen et al., 1995). Since 1989, green crabs have greatly expanded their West Coast range and are now established in bays and estuaries stretching from Monterey Bay, California, to Brooks Peninsula, British Columbia (Jamieson, 2006; Gillespie et al., 2007). Gillespie et al. (2007) notes that the established population of European green crab on the West Coast of Vancouver Island increases the risk of spread of the species to Northern British Columbia and potentially Alaska. These crabs are hardy, voracious predators that consume a broad range of shellfish and other organisms and are capable of out-competing native species for food. The green crab's eating and burrowing habits, combined with its high reproductive rate and potential for dispersal, have raised concerns about the possibility of future invasions and their ecological and economic consequences.

The methodology described in this report links ecological models of green crab impacts on ecosystem services with economic models that value changes in the ecosystem services affected by green crabs. The ecological submodels incorporate green crab dispersal and the relationship between green crab abundance and the abundance of prey populations. The economic analysis estimates the economic consequences, primarily those on commercial and recreational shellfishery harvests and estuary restoration efforts.

2. Green Crab Ecology and Dispersal

2.1 Green Crab Life History

Green crabs are smaller than most commercial species, with adult carapace width ranging from 6 to 10 centimeters (USGS, 2006). In both Europe and Maine, the green crab tends to mature at 2 to 3 years of age and has a lifespan of 3 to 6 years (WDFW, 2002; Yamada et al., 2001). Yamada et al. (2005) found that while green crabs on the West Coast tend to have a similar lifespan to their European and Maine counterparts (4 to 6 years), they mature faster and grow larger. Whereas green crabs in Europe and in Maine mated for the first time at about 2 years of age, crabs in Oregon and Washington reached sexual maturity and mated before the age of 1 year (Yamada et al., 2005).

Mature female green crabs tend to mate one to two times per year. A green crab female can produce more than 185,000 eggs per reproductive event (Green Crab Control Committee, 2002). Assuming two reproductive events per year, a single female may produce as many as 370,000 eggs per year. Cohen et al. (1995) report somewhat lower reproductive rates, estimating that a mature female produces a total of 185,000 to 200,000 eggs per year (Cohen et al., 1995).

2.2 Green Crab Habitat

Green crabs are capable of surviving in water temperatures ranging from 0°C to 30°C and in salinities ranging from 1.4 to 54 parts per thousand (ppt), though they are generally found in waters with salinities of 10 to 33 ppt. Reproduction can occur at 3°C to 26°C and “successful development generally increases with increasing salinity” (Green Crab Control Committee, 2002). At colder temperatures, green crab eggs tend to be less tolerant of low salinity levels (Cohen et al., 1995). In general, postlarval *C. maenas* are more tolerant of extreme temperatures and salinities than the larvae (Green Crab Control Committee, 2002).

In addition to their ability to survive in a broad range of temperatures and salinities, *C. maenas* are also tolerant of a variety of habitats. According to the Green Crab Control Committee, “postlarval crabs occur abundantly in the intertidal and subtidal zone, occurring as deep as 55m. They occur in unstructured sandy and muddy bottoms, are commonly found in saltmarshes and seagrass beds, and also utilize woody debris and rocky substrate” (Green Crab Control Committee, 2002). Although these crabs tend to prefer sheltered bay/estuarine waters less than 20 feet deep, they can also survive in most outer coast environments and have been found as deep as 180 feet (Cohen, 1997).

Natural predators may impact the green crab’s habitat selection. For example, unlike on the East Coast and in its native range, green crabs on the West Coast of North America appear to avoid sheltered rocky habitats, instead settling on sand and mud in shallow, protected waters (Green Crab Control Committee, 2002; Cohen, 1997). A study by Hunt and Yamada (2003) suggests that green crab avoidance of rocky habitats may be due to predation, or threat of predation, by the larger native red rock crab, *Carcinus productus*, which inhabits these areas.

2.3 Pathways of Introduction

The green crab's ability to adapt to a broad range of environments and its high reproductive rate make it a "perfect" invasive species (Environmental News Network, 1998). Every invasion, however, requires an introduction pathway, a means through which an invasive organism is transported from one location to another. Although the exact modes of *C. maenas* dispersal on either the East or West Coast of North America are unknown, scientists believe that in both cases, the initial introductions were human-mediated, while later coast-wide dispersal may have occurred via either natural or human-mediated pathways.

2.3.1 Transoceanic Transport

According to Cohen et al. (1995), "there are no records of *C. maenas* found at sea on floating algae or logs," and the planktonic larval stage of *C. maenas* is too short to allow for transoceanic transport via ocean currents. Following a detailed review of *C. maenas* literature, Carlton and Cohen (2003) conclude that "natural transport does not appear to have been responsible for founding any of the transoceanic populations."

The timing of the introductions and genetic testing indicate that the Atlantic North American *C. maenas* population originated from Europe, while the Pacific North American population originated from the *C. maenas* on the East Coast (Bagley and Gellar, 2001). As such, both introductions were most likely human-mediated. These introductions may have occurred via one or more of the following pathways:

- **Ship Fouling/Boring:** Cohen et al. (1995) believe that in the 19th century, the fouling/boring of wooden vessels was the most common dispersal mechanism for *C. maenas*. This was the most likely mode of the initial green crab introduction on the East Coast of North America because juvenile and adult crabs can take refuge among fouling organisms or within holes created by boring shipworms. Since wooden vessels are no longer used, ship fouling/boring is no longer a viable dispersal mechanism.
- **Solid Ballast:** Because *C. maenas* are able to survive for an extended period of time outside of water and without food (60 and 94 days, respectively), they could have survived a transoceanic journey among stones used as solid ballast (Carlton and Cohen, 2003). Today, dry ballast has been replaced with ballast water.
- **Commercial Fishery Product Shipments:** Commercial fishery products, including Atlantic lobsters and baitworms, are packed in seaweed during transport. The seaweed, "which harbor an extensive living invertebrate fauna including *C. maenas*, are routinely discarded into coastal and estuarine waters by anglers, lobster importers and possible restaurateurs" (Carlton and Cohen, 2003). Grosholz (2006) and Cohen (1997) believe that incidental transport with commercial fishery products is the most likely vector for the initial *C. maenas* introduction to the West Coast.
- **Ballast Water:** Although the mesh size of ballast water intake screens is small enough to block adult *C. maenas* from entering ballast water tanks, *C. maenas* larvae and juvenile crabs may be transported via this vector (Carlton and Cohen, 2003; Cohen et al., 1995).

- **Other Transportation-Related Vectors:** According to Carlton and Cohen (2003), *C. maenas* may also travel via modern-day ship fouling — by attaching to the interior of vessel seawater pipes. Another possible vector is the fouling of exploratory drilling platforms (Carlton and Cohen, 2003).
- **Experimental Research:** The organisms may have been accidentally or intentionally released from educational or research institutions (Carlton and Cohen, 2003).

2.3.2 *Coast-Wide Dispersal*

Unlike transoceanic introductions of green crabs, which appear to occur only through human activity, the dispersal of green crabs along a coast once a single viable population has been established may take place through both natural and manmade vectors. Vessel fouling, ballast water, and other human-mediated pathways may continue to transport the crabs up and down the coast, opening the door for colonization of new locations. In addition to these vectors, however, natural transport of crab larvae via ocean currents may also lead to the establishment of new populations.

Green crabs were first discovered in San Francisco Bay in 1989, with one additional specimen collected in Estero Americano, about 45 km to the north (Carlton and Cohen, 2003). Following the El Niño event of 1991 to 1992, they appeared some 120 km north of the bay, in Bodega Harbor. In 1995, they were found 320 km north of Bodega Harbor, in Humboldt Bay. The next expansion did not occur until 1997, when the crabs “leapfrogged” to Oregon (first discovered in 1997), and, almost simultaneously, to Washington State (1998) and British Columbia (1999) (WDFW, 2002; Carlton and Cohen, 2003).

On the West Coast, scientists believe that the green crab expansion beyond San Francisco Bay is primarily attributable to larval transport by ocean currents. According to the Washington Department of Fish and Wildlife (WDFW), “research data strongly suggest that the introductions to Oregon, Washington and British Columbia occurred through larval transport via strong ocean currents associated with an unusually large El Niño event in 1997 and 1998.¹ In addition, spatial data on captured European green crabs in Willapa Bay and Grays Harbor suggest that Coriolis forces may have influenced larval transport by deflecting planktonic European green crab larvae to the south entrance of each bay mouth” (WDFW, 2002).

The green crab specimens collected in Oregon in 1997/1998 indicate that the crabs were introduced into the state’s estuaries at least twice. The specimens collected came from distinct year classes, with larger crabs from the 1995/1996 or the 1996/1997 year classes, and the more abundant smaller specimens from the 1997/1998 year class. According to Yamada et al. (2001),

¹ An El Niño is a climatic phenomenon that occurs, on average, once every 3 to 7 years, and involves the warming of the equatorial Pacific Ocean (Kessler, undated). El Niño events result from the weakening of the trade winds that, under normal, non-El Niño conditions, push warm waters westward across the Pacific toward Indonesia and Australia. As a result, the sea level in the West Pacific is one-half meter higher than in the East, and the water is about 8°C warmer. Since rainfall tends to concentrate over the warmest water, the Eastern Pacific region tends to be relatively dry. During an El Niño, however, the trade winds in the central and western Pacific relax, increasing the water temperature in the eastern Pacific, and leading to warmer winters, increased rainfall, and strong poleward currents along the North and South American West Coast (NOAA, undated; Yamada et al., 2005). In 1997–1998, a particularly strong El Niño produced northward currents of greater than 40 km/day along parts of the West Coast from November to April (Yamada et al., 2001). Yamada et al. (2001) believe that these powerful currents carried green crab larvae from established populations in San Francisco Bay to Oregon and Washington waters.

the correlation between oyster growing activities and the distribution of older *C. maenas* in Oregon estuaries indicates that the older crabs may have been introduced via either the transportation of aquaculture (a human-mediated vector) or via larval transport by ocean currents. Introduction via ballast water appears unlikely since no ballast water exchange takes place at two of the bays where older crabs were found (Yamada et al., 2001).

Unlike older crabs, the new year class (1997/1998) of *C. maenas* most likely arrived in Oregon and Washington waters via larval transport by ocean currents.² Younger crabs were found in Oregon estuaries with and without oyster culture activities (Table 2-1). Based on the number of specimens collected, the older Oregon population of *C. maenas* was simply too small to populate additional water bodies in Oregon and Washington state. Furthermore, the combination of warm water temperatures and strong northward currents provided “extremely favorable [conditions] for larval transport from California,” where the established population may have produced a particularly large number of larvae (Yamada et al., 2001).

Estuary	New Year Class*	Older Year Class(es)*	Oyster Culture	Ballast Water
Tillamook	X	X	Yes	No
Netarts	X	M	Yes	No
Salmon	M		No	No
Siletz	X		No	No
Yaquina	X	X	Yes	Yes
Alsea	X		No	No
Coos	X	X	Yes	Yes
Coquille	X		Yes	No

Source: Table 1 in Yamada et al. (2001).
 * X = Green crabs were found in the estuary. M = Only green crab molts were found in the estuary.

Assuming that the new year class that appeared in Oregon and Washington waters in 1997/1998 originated in San Francisco Bay, the total distance traveled by green crab larvae during this expansion was more than 1,000 km. According to Edwin D. Grosholz (2006), the rate of green crab dispersal can be approximated by estimating the rate of expansion during El Niño events, and assuming relative stasis in non-El Niño years. It is important to note that at least one El Niño event has taken place since green crabs arrived in Oregon and Washington waters (NOAA, 2006a). This event, which occurred in 2002–2003, was not as powerful as the 1997–1998 El Niño, and its impact on the green crab range is unknown.

2.4 Current Range and Potential for Expansion

Based on the green crab’s water temperature tolerance, Carlton and Cohen (2003) estimate that on the West Coast of North America, this invader’s potential range extends from Baja California, Mexico, to just north of the Aleutian Peninsula in Alaska (about 60°N latitude). Carlton and Cohen estimate that on the East Coast, the green crab range will be limited by the southern Gulf of Saint Lawrence (Canada) to the north and by the Chesapeake Bay to the south (Carlton and Cohen, 2003).

² Although El Nino events influence green crab expansion on the West Coast, detailed analysis of El Nino events and ocean currents is beyond the scope of this report.

A recent study by Hitchcock et al. (2004), however, found that green crab larvae are much more sensitive to temperature and salinity. In particular, larvae below 10°C or in a salinity of 20ppt, at any temperature, do not develop. Larvae reared above 22.5°C developed quickly to subsequent molt stages but died before molting to juvenile crab. Therefore, the potential range of green crab expansion may be lower than suggested by previous research.

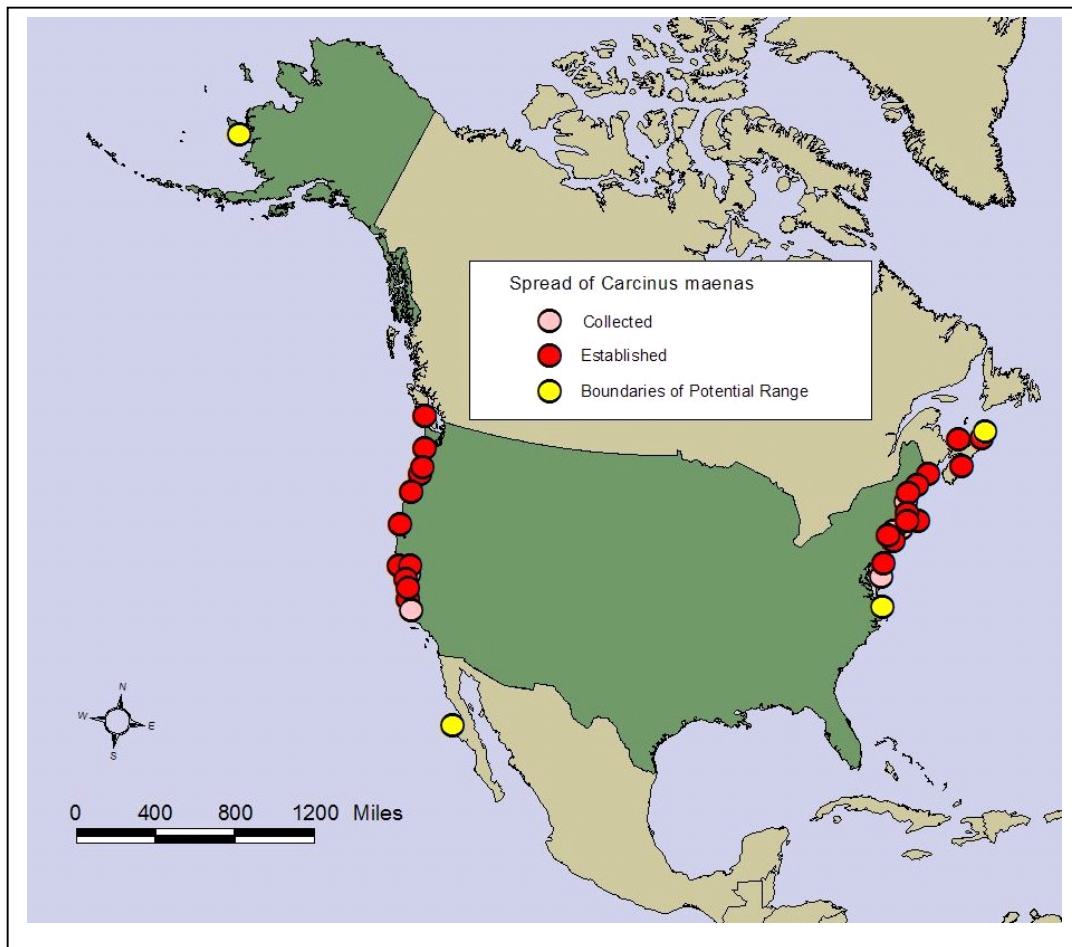
To identify the current and historical habitat range of green crabs, this study relies on empirical data (deRivera, Gillespie, Grosholz, Preissler, Ruiz, Schlosser, Yamada, and Wasson, unpublished data). Exhibit 2-1 compares the current and potential range of *C. maenas* on both North American coasts.

According to the Green Crab Control Committee, while the green crab distribution on the East Coast “is not static,” further expansion on the West Coast is particularly likely (Green Crab Control Committee, 2002).³ As demonstrated in Exhibit 2-1, while on the East Coast green crabs are already established in water bodies along most of the coastal range predicted by Carlton and Cohen (2003), their potential range on the West Coast is significantly larger than the territory they currently occupy. East Coast expansion also appears to be limited by the presence of the native blue crab, *Callinectes sapidus*, which preys on the smaller *C. maenas* (DeRivera et al., 2005). The Asian crab, a new invader on the East Coast, may also compete with the green crab for food and habitat (Tyrell and Harris, 1999; Witlatch, 2006). However, the Asian crab is primarily a rocky intertidal species that is frequently abundant in structured habitats while green crabs are successful in a variety of other habitats not colonized by the Asian crabs. Therefore, the overall impact of Asian crabs on green crab population is likely to be limited (Jensen et al. 2002; McDermott, 1998; Lohrer and Witlatch, 2002).

The potential for expansion on the West Coast is much higher. According to Yamada et al. (2006), “it was hoped that the green crabs would go extinct in the Pacific Northwest once the original colonists reached the end of their lifespan of 4–6 years and no new larvae arrived from California. This has not happened.” (Yamada et al., 2006). On the contrary, a spring 2006 study by Yamada et al. showed that the 2005 year class now forms the dominant cohort of green crabs in the Pacific Northwest. Although the catch per unit effort (CPUE) has declined significantly since 1998, the dominance of the 2005 year class indicates that, assuming a green crab lifespan of six years, a larval source will be available in affected water bodies until 2011. Yamada et al. also note, however, that “while Yaquina, Netarts and Willapa Bay have seen good recruitment in 2005, Grays Harbor [WA] and Coos Bay [OR] (at the extreme of our sampling range) have not.” In fact, in the spring of 2006, the CPUE for Grays Harbor, Washington, was zero. Preliminary data reported by Fisheries and Oceans Canada scientists, however, indicate that green crabs were present in three water bodies in British Columbia: Esperanza Inlet, Clayoquot Sound and Barkley Sound (Yamada et al., 2006). According to Glen Jamieson of the Department of Fisheries and Oceans (Canada), there are established populations of green crabs on the outer coast of Vancouver Island, British Columbia, from Barkley Sound to Brooks Peninsula (Jamieson, 2006; Gillespie et al., 2007).

³ Although the populations of green crab are well established in the Gulf of Maine, green crab densities vary from year to year, possibly due to fluctuations in winter temperatures (Green Crab Control Committee, 2002).

Exhibit 2-1: Current and Potential Range of *C. Maenas* on the East and West Coasts of North America



Source: USGS, 2006; Yamada et al., 2001; Yamada et al., 2005; Grosholz, unpublished data; Holmes, 2001; Hines et al. 2004; Jamieson, 2006; Steves et al., unpublished data; Audet et al., 2003.

2.5 Modeling Probability of Invasion

To estimate the potential future impacts of the European green crab on commercial shellfisheries on the West Coast, we used the Genetic Algorithm for Rule-set Prediction (GARP) model to define the outer boundaries of its potential spread. GARP is a generic algorithm that creates an ecological niche model for a species that represents the environmental conditions where that species would be able to maintain populations (deRivera et al., 2005). To predict the relative probability of invasion for a given site within the specified habitat range we use a logistic regression approach (Havel et al., 2002).

2.5.1 Conceptual Model

The essence of the model developed by Havel et al. (2002) is a likelihood profile technique (Hilborn and Mangel, 1997) that combines a description of both spatial location of uninvaded sites and potential sources as well as a description of local habitat features that may influence the susceptibility of the site to be invaded. This model structure provides a good fit for the discrete spatial distribution of the bays and estuaries that green crabs colonize on the West Coast. The

description of movement in this model assumes that the spread of green crabs along coastlines is a function of passive dispersal. The model also allows for a description of the distance from the source populations to target bays.

To estimate the probability that a susceptible estuary i is invaded (p_i), this study uses the following functional form:

$$p_i = \frac{\exp(a + \mathbf{X}_i\boldsymbol{\beta} + \gamma_1 d_{ik} + \gamma_2 s)}{\exp(a + \mathbf{X}_i\boldsymbol{\beta} + \gamma_1 d_{ik} + \gamma_2 s) + 1} \quad (1)$$

Where the dependent variable is a dummy equal to 1 if the population of crabs is established in an estuary, a is the constant and $\boldsymbol{\beta}$ is the vector of scaling coefficients for the explanatory variables in vector \mathbf{X} ; γ_1 and γ_2 are the coefficients on the spatial variables; d_{ik} is the variable measuring the distance of estuary i from the nearest estuary, k , that has been invaded by green crabs; and the variable s measures the number of adjoining estuaries that have been invaded by green crabs.

The information currently available suggests that green crab establishment is likely to be influenced by a wide range of habitat variables. For ease of exposition, these variables are categorized into those characterizing (1) physical and hydrological characteristics, (2) biological factors, and (3) spatial factors. Attributes included within each category are summarized below.

Physical and hydrological characteristics that describe the adequacy of particular bays and estuaries for invasion by green crabs include watershed area, area of mixing zone, temperature, salinity, dissolved oxygen, and a measure of eutrophication. The selection of physical characteristics for inclusion in the model was based on published primary literature (e.g., temperature, salinity, area of mixing zone), the ability of the variable to describe habitat quality (e.g., dissolved oxygen and eutrophication), and empirical performance of each variable. Although benthic variables, such as moisture, clay, and H diversity index, are likely to affect the likelihood of green crab invasion, adequate data were not available for use in the estimation.

Biological factors such as presence of predators and prey (e.g., shellfish) are also likely to influence the probability of future invasions by green crabs. Green crabs are voracious predators that consume a broad range of shellfish. Although the species may successfully invade waterbodies that don't support shellfish the presence of shellfish may increase the susceptibility of the site to be invaded. Natural predators may also impact the green crab's habitat selection. As noted above, green crab expansion on the East Coast appears to be limited by the presence of the native blue crab, *Callinectes sapidus*, (deRivera et al., 2005). On the West Coast, green crabs tend to avoid areas inhabited by the larger native red rock crab, *Carcinus productus*, (Hunt and Yamada, 2003; Jensen et al. 2007). The presence of Dungeness crab, *Cancer magister*, may affect the behavior of green crab in Northern estuaries (e.g., Willapa Bay) and thus may limit expansion of green crabs on the West Coast (McDonald, 2006; Grosholz, 2007).

Spatial factors such as the distance from all source populations to target bays and estuaries and green crab presence in adjoining estuaries are likely to play an importation role in coastal spread. To account for the sources that are likely to contribute to the larval pool of green crabs that would invade additional water bodies, we considered several spatial variables: (1) the distance to susceptible estuaries from the San Francisco Bay, where the invasion on the West Coast started; (2) the distance to the nearest estuary with green crabs; and (3) the number of adjoining estuaries that have been invaded by green crabs. In addition, larval recruit to a particular waterbodies may depend on oceanographic conditions (e.g., non-El Nino vs. El Nino years), larval development

and behavior (Quieroga et al., 1997). This study does not attempt to incorporate these additional factors due to the lack of data and complexity of the underlying relationships (e.g., changes in larval behavior due to prey availability). The model also does not include a temporal factor due to the lack of data on the timing of invasion in each estuary.

Variables incorporated in the final model are listed and described in Table 2-2. EPA selected model variables based on guidance from prior literature. Also included are additional factors (e.g., pollution) based on expectations that such factors are likely to indicate suitability of a habitat for green crabs.

Table 2-2: Summary Statistics of Model Variables				
Variable Name	Variable Description	Overall Mean	Estuaries with Green Crabs	Estuaries without Green Crabs
<i>Number of observations</i>		<i>111</i>	<i>57</i>	<i>54</i>
Green_present	Dummy variable equal to 1 if green crab is present	0.49	0	
WaterEDA	Estuarine Drainage Area (EDA) (square miles)	154.62	175.35	132.73
Mzone	Mixing zone area (square miles)	84.57	140.61	30.81
Human	Overall human influence. Ordered from 1-5 in increasing order of influence	3.35	3.16	3.52
Temp	Mean surface and bottom temperature (Deg C)	19.39	22.28	17.34
Sal	Mean surface and bottom salinity (psu)	22.42	17.28	26.06
Oxy	Mean surface and bottom dissolved oxygen (mg/L)	7.22	6.83	7.50
Depth	Collection depth at which bottom readings were collected (meters). Proxy for depth of the estuary.	0.62	0.73	0.54
Oth_Crab	Ordered variable measuring the presence of other crabs (0-5) increasing in abundance	1.00	1.39	0.54
Shell_present	Ordered variable measuring number of shellfish varieties present (1-6)	1.97	2.13	1.79
Pol_Flow	Total watershed estimated flow of pollution (mg/year)	1,101,440	769,396.40	1,451,930.00
DisNear	Distance of estuary to nearest estuary with green crab (miles)	0.27	0.12	0.44
Con_Num	Number of adjoining estuaries with green crab presence	1.3	1.61	1.05

2.5.2 Data

The data on physical and hydrological characteristics of bays and estuaries for this analysis came primarily from NOAA's Coastal Geospatial Data project. Each observation in this analysis corresponds to a unique estuary, defined as an Estuarine Drainage Area (EDA) in the NOAA Coastal Geospatial Data. An EDA is that component of an estuary's entire watershed that empties directly into the estuary and is affected by tides. For each EDA, the data on physical and hydrological characteristics included the area of the EDA, mixing zone area, eutrophication characteristics such as human influence, pollution, and shellfish harvest area. The physical and hydrological data are not associated with a specific year; rather, they were described as long-term averages.⁴

In addition to the data we had, information on vector strength would have been important information to include in the analysis since invasion is likely to depend on natural dispersal and hydrology. Therefore, not all sites ecologically amenable to green crabs would be invaded once vector strength is taken into account: this might explain why green crab has not spread to Puget Sound or the Straits despite being abundant in west coast of Vancouver Island. While we were not able to incorporate the hydrological models to explain invasion, we note that this estimation is a step forward because we incorporate biological variables that have not been incorporated earlier paper.

The water area of the coastal estuary (WaterEDA) is measured in square miles and comes from NOAA's Coastal Assessment Framework included in the Geospatial Data.

The mixing zone area (Mzone) was measured as the area of the water component of the EDA where mixing of salinity zones occurs. Salinity in the mixing zone can range from 0.5 to 25 ppt, whereas the salinity within the seawater and tidal zones is relatively uniform.

Eutrophication data, measuring overall human influence (Human) came from the 1991–1992 National Estuarine Eutrophication Survey. These data provide information for assessing the scale and severity of the symptoms of eutrophication based on expert review of the 1991–1992 National Estuarine Eutrophication Survey. The human influence (Human) variable was calculated as the aggregated qualitative value of nutrient input and susceptibility for an entire estuary to eutrophication.

The Environmental Monitoring and Assessment Program (EMAP) National Coastal Database provided information on water *temperature, salinity, and dissolved oxygen* content. The temperature (Temp) for each estuary is a representative long-term average estimated as the average of bottom and surface temperature measurements gathered during the period 1997–2001. The salinity (Sal) for each estuary is also a representative long-term average estimated as the average of bottom and surface salinity measurements gathered during the period 1997–2001. Similarly, the dissolved oxygen (Oxy) is the long-term average of bottom and surface dissolved oxygen for the same period. There was no direct measure of *the depth of the estuary* (Depth). However, information was available on the average bottom collection depth at which the data on temperature, salinity, and dissolved oxygen were measured. This variable was used as a proxy for estuary depth.

⁴ We note that some data (e.g., pollutant discharges and shellfish abundance) represent long term averages from 1980s and 1990s. This is likely to introduce a greater than desirable uncertainty in the analysis, if there were significant changes in the relevant factors in the last decade.

Pollutant flow data that measure the average quantity of pollutant flows into each estuary per year (Pol_Flow) were derived from NOAA's National Coastal Pollutant Discharge Inventory (NCPDI). NCPDI is a national database and computational framework that provides estimates of pollutant discharges from all point, nonpoint, and riverine sources into the estuarine coastal and oceanic waters of the contiguous United States. It approximates pollutant discharge conditions during the period from about 1982 to 1991. Major categories of pollutants included are oxygen-demanding materials, particulate matter, nutrients, heavy metals, petroleum hydrocarbons, pathogens, and wastewater.

The data on *shellfish abundance* were obtained from NOAA's Estuarine Living Marine Resources (ELMR) Database, which contains information from 1985 and 1994. Species in the ELMR database include blue crab, blue mussel, California jackknife clam, Dungeness crab, Manila clam, Pacific littleneck clam, Pacific oyster, soft-shell clam, bay scallop, Eastern oyster, quahog, and sea scallop.

We estimated the average annual abundance rating based on the reported data for all shellfish species at each estuary, where abundance rankings are interpreted as: blank = no data available, 0 = not present, 2 = rare, 3 = common, 4 = abundant, 5 = highly abundant. We estimated a count of the number of green crab prey species present at each estuary (Shell_present), based on their average annual abundance rating, by counting all shellfish species with an abundance rating of at least "rare." We used the average abundance rating to measure the presence of other crabs (e.g., blue crab and Dungeness crab) that prey on or compete for food and shelter with green crabs (Oth_Crab).

Finally, we used a geographic information system (GIS) to estimate the distance to the nearest estuary with green crabs (DisNear) and the number of adjoining estuaries with green crab presence (Con_Num).

Table 2-2 presents the overall mean value of the variables used in these analysis and mean values for estuaries that have been invaded by green crabs and for those that have not.

2.5.3 Results

We modeled the probability that a susceptible estuary would be invaded as a function of measured physical and hydrological characteristics of the estuary (water area, area of mixing zone, temperature, salinity, dissolved oxygen, and estuary depth), eutrophication characteristic (measured by overall human influencing factor), shellfish presence (presence of other crabs that either compete or predate on green crabs and the presence of shellfish), and pollution. Regression results reveal strong systematic elements influencing the probability of green crab invasion. In general, the statistical fit of the equation is quite good; there is a strong systematic element of green crab presence variation that allows forecasting of probability of invasion based on water body characteristics. The R-square is 0.69. Of the 12 independent variables in the model (not including the intercept), 5 are statistically significant at the 10 percent level, with most statistically significant at the 5 percent level. Signs of significant parameter estimates generally correspond with intuition, where prior expectations exist. The results of the logistic regression are presented in Table 2-3.⁵

⁵ Other than a linear model, we also tried the non-linear model proposed by Havel (2002), but we could not achieve convergence in the maximum likelihood to estimate that model.

Table 2-3: Green Crab Presence (Logistic Regression)		
<i>Dependent Variable: Green Crab Presence</i>		
Variable	Coefficient	T-Stat
WaterEDA (miles)	0.01	0.8
Mzone (sq. miles)	-0.01	-0.58
Human (ordered 1-6)	-0.35	-0.64
Temp (Deg C)	-0.98**	-2.49
Sal (mg/L)	-0.07	-0.67
Oxy (psu)	-1.63	-1.56
Depth (meters)	-0.15	-0.93
Oth_Crab (ordered 0-5)	-2.21*	-1.81
Shell_present (1-6)	2.66**	2.06
Pol_Flow (mg/y)	8.7E-07	1.13
DisNear (miles)	-12.49*	-1.94
Con_Num (count)	2.73**	2.43
Constant	33.41**	2.34
Number of Observations: 58 (West Coast-21, East Coast- 37)		
Pseudo R ² : 0.6839		
Log Likelihood -11.81		
* Denotes significance at 10 percent level. ** Denotes significance at 5 percent level.		

Following standard econometric practice, the final model is specified based on guidance from theory and prior literature. Initially, we included all variables for biological factors and physical and hydrological factors aggregated at the primary and secondary level and all the spatial factors that we expected would affect the probability of invasion. We sequentially added variables that distinguished primary and secondary symptoms and found that they did not add any significant explanatory power to the model. For example, variables distinguishing primary (e.g., chlorophyll abundance and macroalgal abundance) and secondary symptoms (e.g., submerged aquatic vegetation loss and toxic algal blooms) added no significant explanatory power to the model. Therefore, we retained the overall eutrophication variable that measured the average effect based on the primary and secondary eutrophication symptoms. Overall a few variables were excluded either because they had a lot of missing observations and were poorly measured (e.g. benthic variables) or because of lack of statistical significance. Individual variables were excluded only if they could not be shown to be statistically significant in any version of the model, and if there was no overriding rationale for retaining the variable in the model.

We also tried regressions with cross produce of temperature and salinity since these two variables together determine the conditions in which green crabs thrive. However, this interaction was found to be insignificant. Further, we expected that the presence of blue crab might be affected by temperature, therefore we tried a cross product of blue crab presence with temperature. However, we found that this effect was significant.

It is important to note that although empirical considerations certainly play a role in model development, certain variables were retained in the model for theoretical reasons, even if significance levels were low. Such specification of regression models using a combination of theoretical guidance and empirical considerations is standard in modeling efforts.

Eight variables are measures of physical and hydrological characteristics of the target bays and estuaries: WaterEDA, Mzone, Temp, Sal, Oxy, Depth, Human, Pol_Flow. Most variables are of the expected signs. However, only the temperature variable (Temp) is statistically significant ($p < 0.1$). We find that the probability of green crab presence increases as estuary temperature

(Temp), salinity (Sal), and eutrophication symptoms (Human) decline. The model results indicate that green crabs prefer larger (WaterEDA) and shallower (Depth) bays and estuaries. Three variables (Mzone, Oxy, Pol_Flow) have unexpected signs. For example, the positive parameter estimate associated with pollution flow in a given water body suggests that green crabs prefer more polluted water bodies — a finding that defies simple intuitive explanation. One explanation could be that the native species of crabs – the main competitors of green crabs - are more sensitive to pollution and therefore are less abundant in polluted estuaries.

The model results suggest that biological factors such as presence of shellfish that the green crab preys on and presence of other crabs are significant determinants of the green crab presence in a given water body. The variable Shell_present represents the number of shellfish species that are at least “rare” in the water bodies included in the analysis. The associated parameter estimate is significant ($p < 0.05$) and has the expected positive sign, revealing an increased probability of invasion if the prey species are abundant. Another important and theoretically intuitive finding is that the probability of green crab presence declines as abundance of larger crabs (e.g., Blue Crabs and Dungeness crab) increases (Oth_Crab).

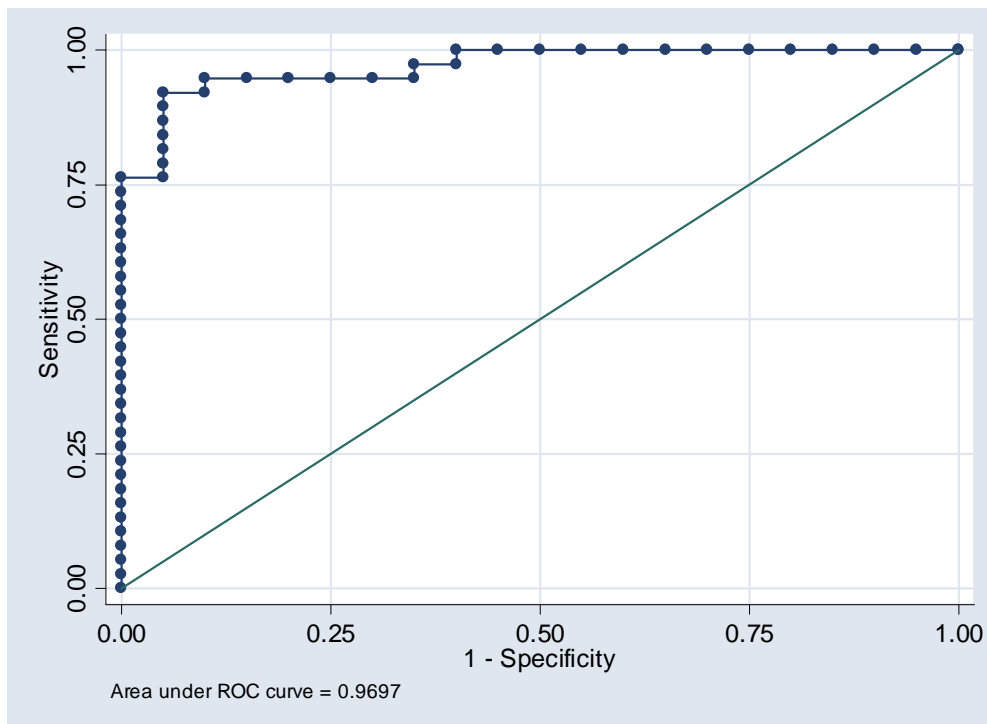
Finally, we find that both the spatial variables (DisNear and Con_Num) are statistically significant at $p < 0.05$, suggesting that the proximity to the source populations of green crabs increases the probability of green crab invasion. In this analysis we did not have information on the timing of invasion, therefore we are unable to distinguish between green crab populations that are well established versus those that were established later on. Therefore the two spatial variables may underestimate the effect of proximity since they do not capture this variability – estuaries that are closer to estuaries with well established green crab populations would be more susceptible to invasion than otherwise. However, this suggests that, if anything, the spatial effect would be stronger.

Overall, the estimated regression suggest that green crabs are not very sensitive to adverse environmental conditions such as pollution and that they would invade nearby estuaries if food is abundant, the population of other crabs is relatively low and temperature and salinity are right. Appendix C presents the estimated probabilities of estuary infestations of estuaries that are not currently infested.

We also conducted a Relative Operating Characteristic (ROC) analysis to assess if the model predicts better than a random prediction. The ROC curve (see Exhibit 2-2) plots the fraction of true positives (Sensitivity) on the fraction of false positives (1-Specificity). Where the true positive are cases of classifying invasion correctly among estuaries that have established green crab populations and false positive measure the number of incorrect positives in estuaries that do not have established green crab presence. The ROC space therefore, depicts the relative trade-offs between true positives and false positives.

The best possible prediction method would yield a point in the upper left corner or coordinate (0,1) of the ROC space, when all true positives are found and there are no false positives.). A completely [random guess](#) would give a point along a diagonal line - *line of no-discrimination*) from the left bottom to the top right corners. Points above the diagonal line indicate good classification results, which is true for our case.

Exhibit 2-2: ROC Analysis



The ROC analysis above suggests that our model does well to predict the true positives while minimizing the false positives.⁶ We also note that for six out of seven data points on the estuaries south of Cape Hatteras, our model predicts accurately that green crabs will not be present. Table C-1 in Appendix C provides the predicted probability of infestation for all estuaries in the model.

This study uses the results of the estimated statistical model, in conjunction with information specific to the potentially targeted bays and estuaries, to estimate the probability of green crab invasion of the West Coast estuaries that do not currently have established green crab populations.

3. Overview of Ecological Impacts of the Green Crab

The establishment of any invasive species has the potential to cause significant ecological and economic damage to the host ecosystem. Because invasive species are typically without their native competition and predators, their populations can grow rapidly once introduced, given the right conditions. For the European green crab, *C. maenas*, these hospitable conditions are available on both the eastern and western coasts of North America, as described in Section 2.4.

Since its initial introduction and establishment in North America, the European green crab has been associated with the decline of a number of native aquatic species. Studies reveal that *C. maenas* eats a variety of organisms including species from at least 104 families and 158 genera

⁶ As suggested by reviewers of the earlier version of this report, we considered using the East coast model to predict the West coast probabilities of invasion. Such analysis, however, was not feasible because the two areas are different and an East Coast model does not apply well to the West coast. Therefore, it is more relevant to look at how a model that uses East and West coast data predicts the probability of green crab presence relative to actual occurrence.

within 14 animal and 5 plant and protozoan phyla. An examination of the stomach contents of *C. maenas* reveals that its main prey includes mussels, clams, worms, snails, seaweeds (algae), barnacles, isopods, and other crustaceans (Cohen, 1997).

Table 3-1 presents a list of some species potentially affected by *C. maenas*, including both those species directly impacted as prey and those indirectly impacted via disturbances to their ecosystems.

While the ultimate extent of the damage caused by invasive European green crabs is not yet known, available information does suggest that their presence in North America has affected or has the potential to affect a number of ecosystem goods and services, including:

- **Habitat Functions:** the availability and preservation of a healthy ecosystem that provides habitat to support biological diversity
- **Production Functions:** the processing of nutrients, energy, water, and gases through the ecosystem, beginning with photosynthesis
- **Regulation Functions:** the bio-geochemical cycles and biospheric processes that maintain the ecosystem
- **Recreation Functions:** the recreational services provided to humans by the ecosystem.⁷

The remainder of Section 3 explores in more detail these ecosystem services and how they either are or could be impacted by *C. maenas*.

3.1 Habitat Functions

Habitat functions include ecosystem services that contribute to the provision of suitable habitat for native plants and animals to successfully live and reproduce. The refugium functions of an ecosystem are the qualities that make it a suitable place for organisms to live, while the nursery functions are those qualities that successfully support organisms' reproductive processes. The introduction and establishment of *C. maenas* in North America has interfered with these habitat functions for a number of different organisms.

⁷ These categories of ecosystem goods and services were adapted from those described in de Groot et al. (2002).

Ecological and Economic Impacts and Invasion Management Strategies for the European Green Crab

Table 3-1: Species Potentially Affected by <i>C. maenas</i>		
Scientific Name	Common Name	Source
<i>Algamorda subrotundata</i>	Newcomb's littorine snail ¹	Holmes, 2001
<i>Argopecten irradians</i>	Scallops	Green Crab Control Committee, 2002
<i>Cancer irroratus</i>	Rock crabs	Lafferty and Kuris, 1996
<i>Cancer magister</i>	Dungeness crab	Lafferty and Kuris, 1996
<i>Crassostrea gigas</i>	Pacific oyster (also known as Japanese oyster)	Holmes, 2001
<i>Cryptomya californica</i>	California soft-shell clams	Palacios and Ferraro, 2003
<i>Cumella vulgaris</i>	Cumacean	Grosholz and Ruiz, 1995
<i>Ensis Directus</i>	Atlantic jackknife clam	Grunden, 2006
<i>Gemma gemma</i>	Eastern gem clam	Grosholz, 2005
<i>Geukensia demissa</i>	Marsh mussel	Lafferty and Kuris, 1996
<i>Hemigrapsus oregonensis</i>	Small grapsid crab	Grosholz and Ruiz, 1996
<i>Katelysia scalarina</i>	Venerid clam	Walton et al., 2002
<i>Leptocheilia dubia</i>	Tanaid	Grosholz and Ruiz, 1995
<i>Littorina littorea</i>	Periwinkle	Leonard et al., 1998
<i>Macoma nasuta</i>	Bent-nosed macoma clams	Palacios and Ferraro, 2003
<i>Mercenaria mercenaria</i>	Quahog/Hard-shell clam	Green Crab Control Committee, 2002
<i>Mya arenaria</i>	Soft-shell clam	Lafferty and Kuris, 1996
<i>Mytilus edulis</i>	Blue mussel	Davis et al., 1998
<i>Mytilus trossulus</i>	Native mussel	Grosholz and Ruiz, 1995
<i>Nucella lapillus</i>	Snail	Grosholz and Ruiz, 1995
<i>Nutricula confusa</i>	Native CA clam	Grosholz et al., 2000
<i>Nutricula tantilla</i>	Native CA clam	Grosholz et al., 2000
<i>Ostreola conchaphila</i>	Olympia oyster	Palacios and Ferraro, 2003
<i>Panopea abrupta</i>	Geoduck clam	Holmes, 2001
<i>Phoronopsis viridis</i>	Phoronid	Grosholz and Ruiz, 1995
<i>Pleuronectes vetulus</i>	Juvenile English sole	Jamieson et al., 1998
<i>Potamocorbula amurensis</i>	Introduced Asian clam	Grosholz and Ruiz, 1995
<i>Protothaca staminea</i>	Pacific Littleneck clam	Holmes, 2001
<i>Saxidomus giganteus</i>	Butter clam	Holmes, 2001
<i>Semibalanus balanoides</i>	Barnacle	Leonard, Ewanchuk, and Bertness, 1999
<i>Siliqua patula</i>	Razor clam	Holmes, 2001
<i>Tapes japonica</i>	Japanese cockle	Lafferty and Kuris, 1996
<i>Transennella confusa</i>	Confusing transennella	Grosholz and Ruiz, 1995
<i>Transennella tantilla</i>	Purple transennella	Grosholz and Ruiz, 1995
<i>Venerupis philipinarum</i>	Manila clam (also known as Japanese littleneck clam)	Grosholz et al., 2001
<i>Zostera marina</i>	Eelgrass	Davis et al., 1998

Note: This table does not list all species potentially affected by the European green crab.
¹ Washington Listed species (Endangered, Threatened, or Sensitive) or Washington Candidate species (to be reviewed for possible listing) (Holmes, 2001).

3.1.1 *Refugium Functions: Disruption of Physical Habitat*

Eelgrass (*Zostera marina*) forms beds responsible for a number of functions important in maintaining a healthy ecosystem (Davis et al., 1998). For example, the juvenile Dungeness crab (*Cancer magister*) requires epibenthic structures like eelgrass or macroalgae for shelter (McDonald et al., 2001). For reasons such as this, seagrasses like eelgrass are protected under Section 404(c) of the Clean Water Act (33 U.S.C. 1341-1987) (Davis et al., 1998). During high tide on the eastern coast of North America, the European green crab will move from the shallow subtidal habitats to the intertidal mud flats in search of food. While foraging, *C. maenas* reworks the uppermost portion of sediments in the intertidal mud flats. This may cause damage to the estuarine and coastal ecosystems because it results in the cutting and tearing of eelgrass shoots' sheath bundles. Nevertheless, there is no conclusive evidence that green crab poses a threat to existing eelgrass beds (Davis et al., 1998).



Although Davis et al. (1998) did not provide evidence of significant damage to existing eelgrass beds, the study found that the green crab's foraging habits may affect the success of eelgrass restoration efforts. For example, during the Great Bay Estuary eelgrass transplant project in New Hampshire, green crab disturbance resulted in the total loss of acre-size restoration plots in less than 1 month (Short, 2007). A laboratory study undertaken to further investigate the impacts of green crabs on restoration efforts demonstrated potential losses of as much as 39 percent of the transplanted eelgrass within 1 week of green crab exposure (Davis et al., 1998).

Similarly, the burrowing activities of the European green crab in marshes could lead to bioerosion and the destabilization of marsh channel banks (Lafferty and Kuris, 1996).

Section 6 presents a case study of green crab impacts on eelgrass restoration efforts.

3.1.2 *Refugium Functions: Disruption of Food Chain*

While the European green crab can affect the refugium functions of an ecosystem by physically disturbing the habitat, its predation on specific species can also lead to alterations in the host environment and disruptions to the food chain. Many of the species the European green crab preys upon along the western coast of North America are functionally important to the embayments of Washington, Oregon, and California. For example, a number of the small bivalve species that *C. maenas* preys upon are important sources of food for Dungeness crabs, surfperches, and migratory shorebirds. European green crabs also prey upon the tanaid *Leptochelia dubia*, which builds tubes that alter the characteristics of sediments and provide habitat for other organisms (Grosholz and Ruiz, 1995; Grosholz and Ruiz, 1999; Grosholz et al., 2000).

In California bays, the European green crab preys on two native shellfish species whose populations, prior to being depleted by the European green crab, provided competition that moderated the population of the invasive gem clam. Now, after having been in California Bay for 50 years without causing any noticeable damage, the invasive gem clam has begun replacing

native clam species as a result of green crab predation on competing species (Grosholz, 2005).⁸ The spatial extent of the replacement is, however, likely to be limited (Jensen et al. 2007).

3.1.3 *Nursery Functions*

In addition to its ability to alter ecosystems' habitat functions via interference in refugium functions, *C. maenas* can also affect other species' reproductive success. On the West Coast of North America, *C. maenas* often lives on the soft bottoms of protected bays. The Dungeness crab uses the same environment as a nursery area, which results in the exposure of juvenile Dungeness crabs to the European green crab. Some studies suggest (Lafferty and Kuris, 1996) that this may place the juvenile Dungeness crabs at risk from both direct predation from *C. maenas* and from competition for the same small epibenthic invertebrate food source. More recent studies, however, did not find empirical evidence that green crabs pose threat to nursery areas of juvenile Dungeness crab (McDonald et al., 2001; Hoaglund and Jin, 2006).

On the East Coast of North America, *C. maenas* inhabits rocky shores on semi-exposed and wave-protected shores, mudflats, estuarine tidal marshes, and cobble beaches. It has been noted that when *C. maenas* is abundant in these environments, other young species have problems establishing themselves, including urchins, cockle beds, young mussels, and barnacles (Hunt and Yamada, 2003).

3.2 *Production Functions*

Production functions include those ecosystem goods and services involved in the processing of nutrients, energy, water, and gases through the ecosystem, beginning with photosynthesis. Specific production functions of ecosystems that could be affected by *C. maenas* include food production. Experimental studies of green crab predation showed that green crabs resulted in lower levels of sediment chlorophyll *a*, total sediment organic material, and redox compared with control areas (Neira et al., 2006).

3.2.1 *Negative Impacts on Production Functions*

As demonstrated in Table 3-1, the list of species affected by the green crab includes some of the most popular commercially and recreationally harvested clams, mussels, and finfish in the United States. Existing studies show that green crab predation has the potential to greatly reduce the population size of affected species. For example, the green crab is still considered a major threat to shellfish in Martha's Vineyard, where the crab preys on the bay scallop, quahog, and steamer clam — three commercially viable species. In 2001 on Martha's Vineyard, green crabs were shown to consume up to 39 percent of hard-shell clams at the study site over 4 days (Walton, 2003). In Tomales Bay, green crab predation resulted in losses of nearly 40 percent of the annual production of 5,500 kg of Manila clams for one producer in 1996 (Grosholz et al., 2001).

Soft-shell clams and blue mussels are some of the crab's preferred food sources (see Exhibit 3-2). Existing studies show that green crab predation has the potential to greatly reduce the population size of affected species. For example, the green crab is still considered a major threat to shellfish in Martha's Vineyard, where the crab preys on the bay scallop, quahog, and steamer clam — three commercially viable species. In 2001 on Martha's Vineyard, green crabs were shown to consume up to 39 percent of hard-shell clams at the study site over 4 days (Walton, 2003). In

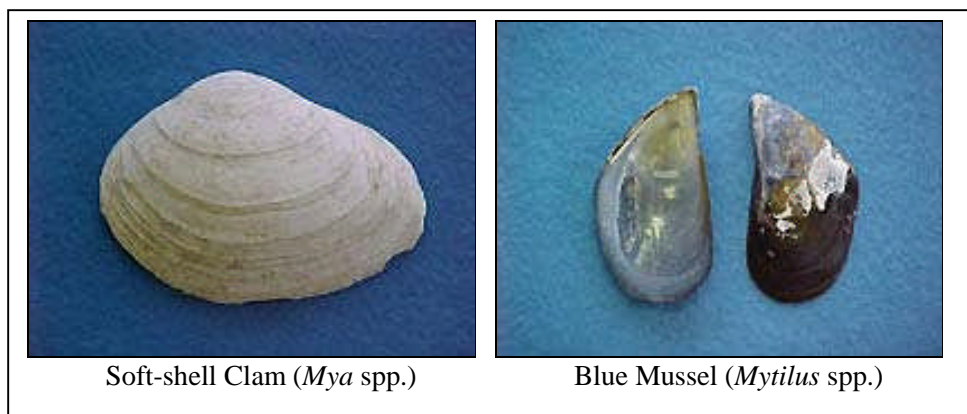
⁸ This service could also be classified under the regulation functions as a biological control based on the categories of ecosystem goods and services described in de Groot et al. (2002).

Tomales Bay, green crab predation resulted in losses of nearly 40 percent of the annual production of 5,500 kg of Manila clams for one producer in 1996 (Grosholz et al., 2001).

Exhibit 3-2 In addition, the crab preys on winter flounder, northern quahogs (hard-shell clams), bay scallops, Manila clams, Pacific littleneck clams, oysters, razor clams, and various other mollusks also consumed by humans. It is important to note that while green crabs have been documented to consume all of these species, quantitative data on the impacts of this predation are currently available for only five shellfish species (hard-shell clams, soft-shell clams, Manila clams, bay scallops, blue mussels), and one finfish species (winter flounder).

Existing studies show that green crab predation has the potential to greatly reduce the population size of affected species. For example, the green crab is still considered a major threat to shellfish in Martha’s Vineyard, where the crab preys on the bay scallop, quahog, and steamer clam — three commercially viable species. In 2001 on Martha’s Vineyard, green crabs were shown to consume up to 39 percent of hard-shell clams at the study site over 4 days (Walton, 2003).⁹ In Tomales Bay, green crab predation resulted in losses of nearly 40 percent of the annual production of 5,500 kg of Manila clams for one producer in 1996 (Grosholz et al., 2001).

Exhibit 3-2: Two Preferred Food Sources of *C. maenas*



Such reductions, in turn, can have significant economic consequences. Table 3-2 and Table 3-3 present the 2001–2005 East and West Coast landings, respectively, of shellfish species for which quantitative data on green crab damage are available.

Year	Northern Quahogs		Soft-shell Clams		Blue Mussels		Bay Scallops	
	Millions of Pounds	Millions of 2006\$	Millions of Pounds	Millions of 2006\$	Millions of Pounds	Millions of 2006\$	Millions of Pounds	Millions of 2006\$
2001	59.6	\$41.8	16.5	\$19.7	13.5	\$3.0	0.0	\$0.1
2002	58.2	\$33.0	15.3	\$17.0	23.5	\$4.6	0.0	\$0.0
2003	61.0	\$37.9	15.4	\$18.8	21.0	\$4.9	0.0	\$0.1
2004	70.8	\$36.7	16.3	\$19.8	20.1	\$3.5	0.1	\$0.2
2005	34.5	\$27.8	16.6	\$21.4	17.7	\$2.9	0.8	\$1.3
5-Year Average	56.8	\$35.4	16.0	\$19.3	19.2	\$3.8	0.2	\$0.3

Source: NOAA, 2006; Pritchard, 2007.

⁹ Losses of 39 percent were recorded at green crab densities of 20.67 and 27.33 CPUE.

Table 3-3: Annual Commercial Fishing Landings for the West Coast (Pounds and Ex-Vessel Value)

Year	Manila Clams		Blue Mussels		Pacific Littleneck Clams		Soft-Shell Clams	
	Millions of Pounds	Millions of 2006\$	Millions of Pounds	Millions of 2006\$	Millions of Pounds	Millions of 2006\$	Millions of Pounds	Millions of 2006\$
2001	7.05	\$8.01	1.95	\$1.64	0.24	\$0.38	0.22	\$0.23
2002	7.33	\$8.50	1.35	\$1.75	0.27	\$0.36	0.65	\$0.25
2003	7.30	\$8.44	2.28	\$2.27	0.17	\$0.32	1.12	\$0.43
2004	7.99	\$9.08	2.73	\$2.38	0.16	\$0.27	0.70	\$0.26
2005	9.14	\$10.12	2.52 ^a	\$1.92 ^a	0.16	\$0.20	0.93	\$0.38
5-Year Average	7.76	\$8.83	2.17 ^a	\$1.99 ^a	0.20	\$0.31	0.72	\$0.31

a. Underestimates value because 2005 data on California blue mussel landings are not yet available.
Source: NOAA, 2006; Pritchard, 2007; and data provided by Alaska, California, Oregon, and Washington.

As demonstrated in Table 3-3, the combined West Coast landings of Manila clams, blue mussels, soft-shell clams and Pacific littleneck clams are worth about \$11.13 million per year. Thus, even a small reduction in harvest due to green crab predation may lead to significant losses in producer's revenue. For example, one percent reduction in harvest would lead to a reduction of more than \$100,000 in fisherman revenues (assuming that a one percent decrease in harvest would not result in price change). East Coast landings for the fisheries summarized in Table 3-2 are worth \$58.8 million per year; a 1 percent reduction in harvest on both coasts would thus decrease revenues by just under \$700,000.

3.2.2 Positive Impacts on Production Functions

In addition to some of the more detrimental impacts *C. maenas* is thought to have on various species consumed by humans, there is growing evidence that *C. maenas* may also have beneficial impacts as a direct food source for humans and as fishing bait. In Japan, *C. maenas* is cut in half and added to miso soup (Lafferty and Kuris, 1996). Additionally, *C. maenas* is sometimes recommended when preparing Spanish paella.¹⁰ While *C. maenas* may not be widely consumed by humans in the United States, it has a history of use as a source of bait for fishing purposes. Green crabs may be used as supplemental bait for the northern conch; for example, a local fisherman in Oak Bluffs, Martha's Vineyard, is currently working on establishing a fishery for these purposes (Grunden, 2006).

Records of annual commercial fishing landings from 1960 to 2004 for *C. maenas* support the theory that there may also be some beneficial impacts associated with this species. As can be seen in Table 3-4, there have been landings for *C. maenas* in five northeastern states: Connecticut, Maine, Massachusetts, New Hampshire, and Rhode Island. Over this 45-year period, total state landings have ranged from almost 23,000 pounds to approximately 570,000 pounds. Although, state-level landings remained stable in some states over that period (e.g., Connecticut) total reported annual commercial landings in northeastern states declined from 108,900 pounds in 1960 to 136 pounds in 2004. While the purpose of these landings is not reported, the two most likely uses are either as food for humans or as bait for fishing. Whatever the use may have been, the cumulative value of landings for these five states over a 45-year period totals almost \$700,000

¹⁰ A recipe for paella on an Australian Web site specifically mentions using green crabs; available here: <http://www.aussieorganics.com/page.asp?parentid=55&parent2id=102&parent3id=77>, accessed November 21, 2006.

(2005\$) and can be considered an example of a potential source of beneficial effects from *C. maenas*.

Table 3-4: Total Commercial Fishing Landings for <i>C. maenas</i> from 1960 to 2004^a		
State	Landings (pounds)	Landings (2005\$)
Connecticut	173,376	\$89,897
Maine	22,799	\$14,476
Massachusetts	298,700	\$202,595
New Hampshire	569,815	\$276,630
Rhode Island	117,300	\$115,633
Total	1,181,990	\$699,232
<i>Source:</i> NOAA, 2005.		
a. Catch from bounty programs is not included in these estimates.		

3.3 Regulation Functions

Regulation functions provided by healthy ecosystems that could potentially be impacted by *C. maenas* include nutrient regulation and waste treatment. Because the green crab preys on a number of bivalve species, nutrient regulation and waste treatment could be altered as a result of fewer clams and other bivalve species in the ecosystem. Typically, as soft-shell clams are feeding, they filter out microscopic particles of plankton, detritus, and other organic materials suspended in seawater (Abraham and Dillon, 1986). A reduction in these filtration rates could then influence the turnover and availability of nutrients in the ecosystem (Grosholz et al., 2000).

3.4 Recreation Functions

Recreation functions include all recreational services provided to humans by an ecosystem. As mentioned in Section 3.2.1, a variety of species the green crab preys upon are commercially harvested. Some of these species are also caught recreationally, such as the soft-shell clam in New England (Abraham and Dillon, 1986). A reduction in the number of available recreational species could correspond to a reduction in the number of organisms caught and the associated marginal decreases in utility experienced by individuals participating in recreational activities. Potentially, the abundance of some species used as bait could also be affected (Lafferty and Kuris, 1996).

As mentioned in Section 3.1.2, the green crab preys upon many aquatic species that also serve as a food source for migratory shorebirds. Thus, other recreational activities that could be affected include bird watching. For example, in Bodega Harbor, California, a significant decline in the population of shorebirds was observed following a reduction in the number of benthic invertebrates that resulted from predation by the Dungeness crab (Grosholz and Ruiz, 1996). However, another study contradicted this finding. Grosholz et al. (2000) conducted a 9-year study of the impact of green crabs on more than 20 species of native invertebrate and at least 13 species of shorebirds in Bodega Bay Harbor, California. Grosholz et al. (2000) found no significant change in shorebird abundance following the green crab invasion at Bodega Bay Harbor, despite declines in some invertebrate populations. Because the change in shorebird population caused by green crab expansion is likely to be negligible, this case study does not attempt to estimate changes in the value of bird watching.

The researchers predict, however, that an increase in local impacts or further expansion of the green crab’s range will result in “bottom-up” effects on shorebird populations (Grosholz et al., 2000).

4. Modeling of Green Crab Impacts on Commercial Shellfish

Commercial impacts of green crab predation on commercial shellfish have been documented for the soft-shell clam, bay scallop, hard-shell clam, blue mussel, and Manila clam shellfisheries.¹¹ The commercial shellfishing damage estimates in this study included all five of these species, as well as Pacific littleneck clams, which are genetically similar to the hard-shell clam and are thus likely to be subject to comparable levels of green crab predation. The common and scientific names of the species considered in this analysis are presented, by region landed, in Table 4-1.

East Coast		West Coast	
Common Name	Scientific Name	Common Name	Scientific Name
Soft-shell clams	<i>Mya arenaria</i>	Soft-shell clams	<i>Mya arenaria</i>
Blue mussels	<i>Mytilus edulis</i>	Blue mussels	<i>Mytilus edulis</i>
Hard-shell clams	<i>Mercenaria mercenaria</i>	Manila clams	<i>Venerupis philipinarum</i>
Bay scallops	<i>Argopecten irradians irradians</i>	Pacific littleneck clams	<i>Protothaca staminea</i>

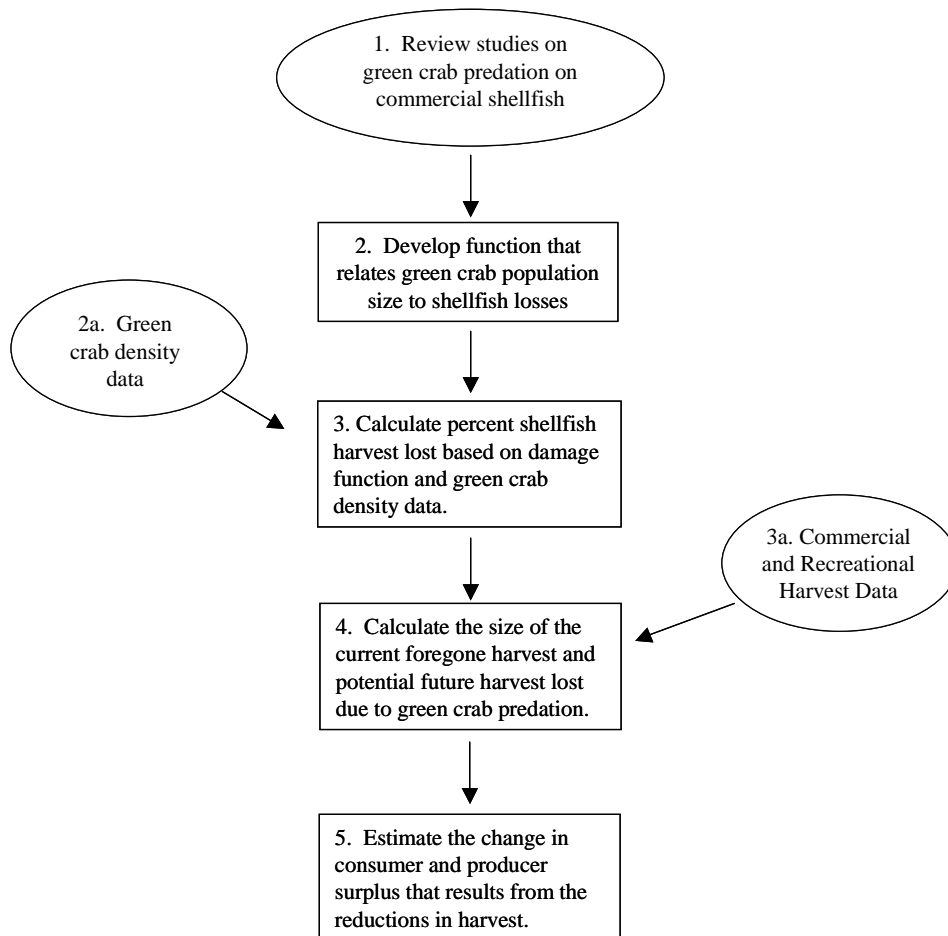
The remainder of Section 4 describes the steps taken and the data sources used to estimate the reductions in commercial harvest due to green crab predation and the economic value of these losses.

4.1 General Methodology

Exhibit 4-1 presents the basic steps used to estimate the reductions in the commercial and recreational shellfish harvest resulting from green crab predation. Shellfish damage functions, green crab densities, and sources of commercial and recreational shellfish harvest data are discussed in more detail in subsequent sections of this report.

¹¹ Although there are also documented historical and current impacts of green crabs on the oyster shellfishery and the winter flounder fishery, damage functions for these species are not currently available, and therefore their damages are not included in the estimated losses.

Exhibit 4-1: Steps Used to Estimate Fishery Losses Due to Green Crab Predation



4.2 Shellfish Damage Functions

Because standard “fisheries” models (e.g., predator-prey) do not apply to managed shellfishery stocks that are largely determined by human economics, this study relies on simple statistical “models” such as logistic regressions to describe the functional relationship between green crab abundance and the dynamics of prey populations.

4.2.1 Data Sources

The data used in the analysis came from six species-specific studies on the effect of European green crab densities on shellfish losses. These studies include an examination of the losses of the following species:

1. Soft-shell seed clams (*Mya arenaria*) in Rowley River, Massachusetts, in 2001 (Massachusetts Department of Fish and Game, unpublished data)
2. Soft-shell clams (*Mya arenaria*) in the southern Gulf of Saint Lawrence (Floyd and Williams, 2004)
3. Manila clams (*Venerupis philipinarum*) in Tomales Bay, California, from 1996 to 1999 (Grosholz et al., 2001)

4. Mussels (*Mytilus edulis*) in Menai Straits, North Wales, from 1972 to 1973 (Dare and Edwards, 1976)
5. Northern bay scallops (*Argopecten irradians irradians*) in Poquonock River, Connecticut, from 1983 to 1984 (Tuttlebach, 1986)
6. Hard-shell clams or quahogs (*Mercenaria mercenaria*) in Martha’s Vineyard, Massachusetts, in 2001 (Walton, 2003).

Data on losses for all shellfish were combined, as it is hypothesized that the green crab is indiscriminate across types of shellfish. This hypothesis was tested by including dummy variables for hard-shell and soft-shell clams, which resulted in no statistical difference in the predator-prey functional relationship between the two types of shellfish.

4.2.2 Green Crab Predation Function

To estimate the functional relationship between green crabs and shellfish populations we used the following functional form (Type II predator-prey interaction):

$$\text{Shellfish Losses} = \frac{b_0}{1 + \exp(-b_1 * \text{Crab Density})} \quad (2)$$

Where b_0 and b_1 are the parameters of the functional form that determine the shape of the sigmoid function. In particular, b_0 , which is statistically significant, represents the shellfish losses at which the crabs reach a saturation point and therefore the level at which the losses reach and asymptote at high crab densities. The results shown in Table 4-2 suggest that the level at which the losses reach an asymptote is 42 percent.

Table 4-2: Green Crab Impacts on Shellfisheries – East Coast			
Dependent Variable: Percentage loss of shellfish.			
Independent Variable: Crab Densities			
Parameter	Parameter Estimate	Standard Error	t-statistic
b_0	0.42	0.17	2.51
b_1	0.06	0.12	0.52
Number of Observations: 26 R-Square: 0.66 Adjusted R-Square: 0.63 F(2, 24) = 23.41, Prob >f = 0.0000 Non-linear estimation. Standard errors are asymptotic approximations.			

This functional form, however, did not perform very well for the West Coast scenarios due to significant differences in green crab densities on the East and West Coasts of the United States. ¹²Further statistical analysis demonstrated that the predator-prey relationship is best captured by a Type I linear functional form for low green crab densities and a Type II functional form at high crab densities. Green crab densities are expressed as catch per unit effort (CPUE), which represents relative densities based on generally standard trapping methods. To determine the cutoff point where the damage function shifts from linear to sigmoid, we estimated switching regressions with cutoffs at 10, 20, and 30 crabs CPUE. The model where the cutoff is 30 CPUE was found to fit the data best. Therefore, this study assumes that the predator-prey relationship is

¹² EPA notes that because there was only one data point for the West Coast, a West Coast dummy did not improve the model and thus was not included in the final specification of the model

linear for CPUE below 30 and that it follows a Type II (i.e., sigmoid) functional relationship for CPUE above 30. Therefore, we estimated the following model:

$$\text{Shellfish Losses}_i = \begin{cases} b_0 * \text{Crab Density}_i + e_i & \text{if Crab Density} < 30 \\ \frac{b_1}{(1 + \exp(-b_2 * \text{CrabDensity}_i))} + u_i & \text{if Crab Density} > 30 \end{cases} \quad (3)$$

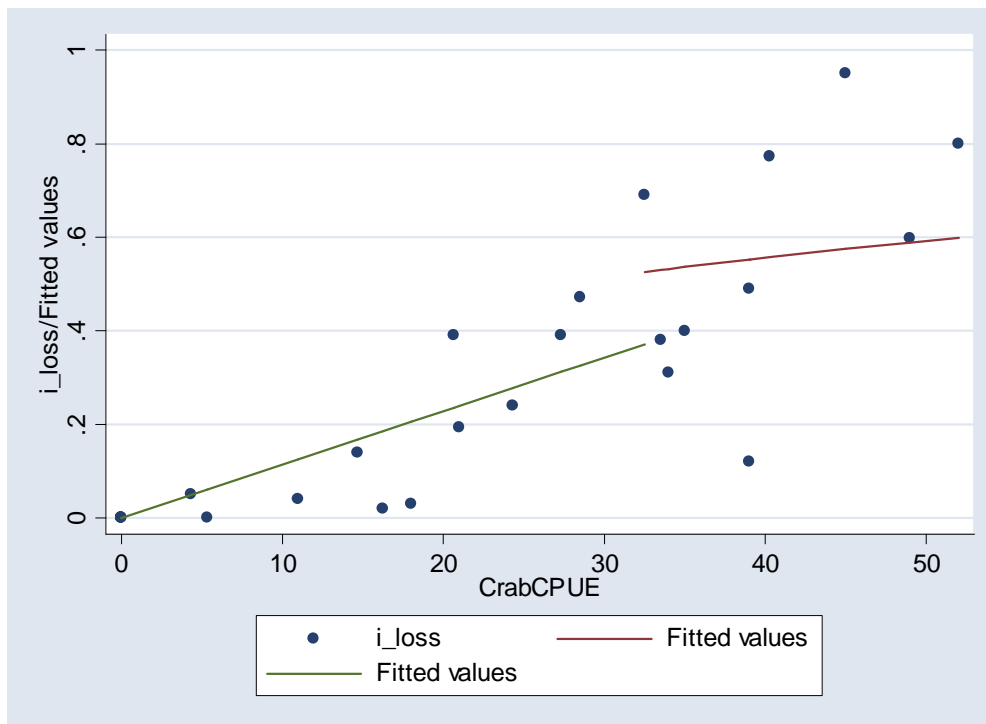
Where b_0 is the parameter of the linear segment and represents the rate at which the shellfish loss increases as crab densities increase; b_1 and b_2 are the parameters of the sigmoid functional form and determine the exact shape of the function; and e_i and u_i are error terms. In particular, b_1 represents the shellfish losses at which the crabs reach a saturation point and therefore the level at which the losses reach an asymptote at high crab densities. The results of this analysis are presented in Table 4-3 and Exhibit 4-2.

The results suggest that for crab densities less than 30, the shellfish loss increases by 0.01 per one unit increase in green crab densities. The statistical fit of the estimated linear equation is good (R-squared equal to 0.81). The crab density variable is statistically significant at $p < 0.01$.

The non-linear equation shows that the shell fish losses reach a saturation point at 72 percent. Although, the estimated parameters of the non-linear predation function (i.e., intercept and Crab Density) are not statistically significant individually, the two variables are jointly significant as shown by F statistics ($F=2317$, Prob $F > f = 0.005$). Therefore, *at least* one of the two variables has a significant influence on the percentage loss of shellfish variable (P, Kennedy, 1992)

Table 4-3: Green Crab Impacts on Shellfisheries – West Coast			
Dependent Variable: Percentage loss of shellfish.			
Independent Variable: Crab Densities			
Parameter	Parameter Estimate	Standard Error	t-statistic
<i>Linear Segment < 30 Crab CPUE</i>			
b_0	0.01	0.002 (robust)	6.2 (robust)
Number of Observations: 16			
R-Square: 0.81			
F(1, 15) = 37.42, Prob >f = 0.0000			
<i>Sigmoid Segment > 30 Crab CPUE</i>			
b_1	0.72	8.13	0.09
b_2	0.03	1.25	0.02
Number of Observations: 10			
R-Square: 0.85			
Adjusted R-Square 0.815			
F(2, 8) = 23.17, Prob >f = 0.0005			
Non-linear estimation. Standard errors are asymptotic approximations.			

Exhibit 4-2: Green Crab Predation Function



4.3 Modeling Commercial Harvest Losses

Green crab impacts on commercial shellfish landings were estimated based on the damage functions discussed in Section 4.2, green crab density ranges,¹³ and data on current and historic landings of the species addressed in this analysis. The shellfish damage functions estimate the percent of shellfish lost based on the size of the green crab population in a particular area. For most species and states, commercial shellfish landings are a combination of shellfish collected in the wild and aquaculture harvest. Because clam farmers generally protect their bivalves using nets or other anti-predator devices, aquaculture losses from green crab predation are likely to be lower than wild harvest losses. According to research conducted by Beal and Kraus (2002) and Beal (2002), anti-predator netting reduces predation losses by between 13 and 54.8 percent. The foregone harvest due to green crab predation was calculated using the following formula:

$$F = [A/(1-X)-A]+[(B/(1-X)-B)*(1-Y)] \quad (4)$$

Where

F = Total annual foregone harvest

A = Actual wild harvest

B = Actual aquaculture harvest

X = Percentage of potential harvest lost to green crab predation (damage function output)

Y = Percentage of losses prevented by aquaculture netting.

¹³ The green crab population size is measured in terms of relative green crab density, or the number of crabs CPUE.

The following sections provide detailed information on the data used in this analysis.

4.3.1 Green Crab Density

East Coast green crab density data were collected from the following three sources:

1. *Status of Green Crabs at eight Atlantic Coast sites (Virginia to Maine) 2001–2002.* Unpublished data collected by Catherine deRivera and colleagues at the Smithsonian Environmental Research Center (deRivera et al. 2006). These data are all trap data collected in ways comparable with data collected currently at other sites. Data were collected and recorded as crabs-per-trap-per-day so CPUE could be calculated and compared with other sites.
2. *Status of Green Crabs in Maine, 1973–1978; 1981–1982.* Data collected by Walter Welch on green crab population densities in the state of Maine. The majority of the data are one man-hour shore samples, which cannot be converted to crabs-per-trap-per-day and thus could not be included in the analysis. Each year, however, several crabs-per-trap-per-day measurements were also available and were included in the estimates.
3. *Seabrook Station Environmental Monitoring Program data, 1978–2004.* Results of green crab sampling conducted at the Seabrook Station in Hampton Harbor, New Hampshire, from 1978 to 2004. All results were in crabs-per-trap-per-day, and all are included in the estimates. (Data obtained from Trowbridge, 2005).

Based on the collected data, green crab densities on the East Coast typically range from 27.40 to 133.15 CPUE.¹⁴ To calculate annual historical and current losses on the East Coast, the random number generator function in Microsoft Excel was used to assign a density between 27.40 and 133.15 CPUE for each year in the time period considered (1975–2005). As such, the analysis assumed that each year, the crab density would fall within the observed range of densities in all affected water bodies. Assigned densities, by year and state, are presented in Appendix A.

On the West Coast, density data are available for select water bodies where sampling was conducted between 1994 and 2006. Non-zero densities recorded on the West Coast range from 0.01 to 31.5 CPUE.¹⁵ Averaged over all years when data were collected (including years when no crabs were caught), green crab population densities range from 0.005 to 15.3 CPUE in northern California, from 0.05 to 1.15 in Oregon, and from 0.06 to 0.14 in southern Washington state. *C. maenas* are currently not found in Alaska, southern California (south of Elkhorn Slough), or northern Washington (north of Grey's Harbor and in Puget Sound), although they are now established on Vancouver Island, British Columbia. West Coast green crab density data were collected from the following two sources:

1. *Status of Green Crabs in Oregon, Washington, British Columbia, and Alaska 1994-2006.* Data collected by numerous individuals including Edwin Grosholz (University of California, Davis), Sylvia Yamada (Oregon State University), Brett Dumbauld (Washington Department of Fish and Wildlife), Graham Gillespie (Fisheries and Oceans Canada), Dan Gilson (Prince William Sound Regional Citizens' Advisory Council), and many colleagues. Data at all sites (unless otherwise specified) were collected and

¹⁴ Recorded densities ranged from 0 to 410 CPUE; 27.40 and 133.15 CPUE are the first and third quartile values.

¹⁵ Density data included a single outlier of 72.33 CPUE, which was dropped from the calculations.

recorded as crabs-per-trap-per-day so CPUE could be calculated and compared with other sites.

2. *Status of Green Crabs in California 1994-2006*. Data were collected by Edwin Grosholz (University of California, Davis), Catherine deRivera (now of Portland State University), Susan Schlosser (California Sea Grant Extension Program), Kerstin Wasson (Elkhorn Slough National Estuarine Research Reserve), and many colleagues.

Because West Coast crab densities vary significantly by state, this analysis estimated current shellfish damages based on each state's average green crab population size. Thus, for California, a density between 0.005 and 15.3 CPUE was assigned at random for each year between 2000 and 2005, while in Oregon, densities between 0.05 and 1.15 CPUE were selected for the same years.¹⁶ Assigned densities, by year and state, are presented in Appendix A.

This analysis assumed that in future years, green crab densities in all invaded areas on the West Coast would be similar to the densities observed during 1994 to 2005. The analysis relied on the random number generator function in Microsoft Excel to assign a population density to the entire West Coast. A density between 0.01 and 31.5 CPUE was assigned at random for each of the 25 years included in estimates of future losses. Because the green crab may not invade some water bodies, the results of the ecological impact analysis were further adjusted to reflect the probability of invasion. These densities are presented in Appendix A.

EPA notes that the purpose of this study is to estimate a range of potential economic damages from green crab impacts rather than to predict specific densities for each estuary. Given that green crab densities vary significantly over a relatively small areas (Jensen et al., 2007) and fluctuate annually, modeling green crab densities was beyond the scope of this study. Therefore, the Agency chose a simplified approach to generating green crab densities for estuaries included in this analysis. To address this limitation, additional uncertainty analysis such Monte Carlo simulations would be desirable as a next step in this analysis.

4.3.2 Commercial Shellfish Harvest Data

This analysis uses the following shellfish harvest data to estimate current and potential future impacts of the green crab on the East and West Coast:

1. Total number of pounds harvested in the wild and the value of the harvest for areas currently invaded by the green crab or that the green crab could potentially invade in the future.
2. Total number of pounds raised and harvested via aquaculture and the value of the harvest for areas currently invaded by the green crab or that could potentially be invaded by the green crab in the future.
3. The percentage of harvest by type of shellfishing gear used for both currently and potentially affected areas.

EPA used one of the following sources to obtain this information:

1. *The National Oceanic and Atmospheric Administration's Annual Commercial Landings by Gear Type*. Reports landings by state, year, and gear type used. Bivalve mollusk

¹⁶ The size of the baseline harvest was estimated based on 2001–2005 landings and green crab densities, with the exception of California, where 2000–2004 blue mussel data were used since 2005 data were not available from NOAA.

- landings are reported in pounds of meats only.¹⁷ Clam and mussel landings include wild and aquaculture harvest.
2. *State commercial landings statistics.* Available from state Web sites and/or through contacts with state departments of fish and wildlife. May be available by port, water body, or only at the state level. Landings generally exclude aquaculture harvest and are reported in whole weight.
 3. *State aquaculture statistics.* Available from state Web sites and/or through contacts with state departments of fish and wildlife. May be available by geographic area or only at the state level. Landings are generally reported in whole weight.

4.3.3 East Coast Shellfish Harvest Data

To estimate damages to commercial East Coast shellfisheries, this analysis relied on NOAA data on landings by gear type for the states of Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey and Delaware.¹⁸ All harvest data are reported at the state level. Current annual harvest losses due to green crab predation were estimated as the average annual losses over the 2001 to 2005 time period. East Coast historical damages were estimated based on 1975 to 2005 landings data.

The majority of the East Coast states included in the analysis do not collect data on shellfish aquaculture. To estimate the percentage of landings derived from aquaculture, this analysis relied on a 2005 presentation given by Richard Langan of the University of New Hampshire (Langan, 2005). Based on this study, 45 percent of the soft-shell and hard-shell clam harvest, and 60 percent of the blue mussel harvest, were derived from aquaculture in 2004. We also used the estimated percentages to calculate the size of the aquaculture harvest for 1985 to 2005. Since aquaculture is a relatively new industry, the analysis assumed that prior to 1985, there were no clam farms in the Northeast. The aquaculture industry is likely to have developed more slowly over a longer period of time. Therefore, these assumptions may lead to an overestimate of the amount of clam farming during 1985 to 2003, and an underestimate of aquaculture in earlier years.

4.3.4 West Coast Shellfish Harvest Data

The green crab is currently present in only part of California and Washington, and it is unlikely to spread to the entire state of Alaska in the future.¹⁹ Thus, the analysis required data on the commercial fishery landings by water body or state region. As such, the West Coast analysis relied on fishery data collected directly from the state departments of fish and wildlife (either via the web, or by contacting the relevant agencies). In most cases, both wild and aquaculture harvest data were available from state agencies. Data provided by states were supplemented with NOAA landings statistics where state information was not available.

¹⁷ On the West Coast, landings in pounds of meats were converted to include shell weights using conversion factors provided by Elizabeth Pritchard at NOAA's National Marine Fisheries Service (NMFS).

¹⁸ Note that although the green crab is also present in northern Maryland (north of the Chesapeake Bay), Maryland's landings were excluded from the analysis because the state was unable to provide data on landings by water body or region.

¹⁹ Based on the green crab's water temperature tolerance, Carlton and Cohen (2003) estimate that on the West Coast of North America, this invader's potential range extends from Baja California, Mexico, to just north of the Aleutian Peninsula in Alaska (about 60°N latitude).

4.3.5 Estimated Historical and Current Commercial Harvest Losses on the East Coast

Table 4-4 presents the historic and current commercial harvest losses on the East Coast, by species. As demonstrated in the table, between 1975 and 2005, East Coast shellfishers have lost between 67.5 and 77 million pounds of quahogs, soft-shell clams, blue mussels, and bay scallops to green crab predation each year. The estimated current annual losses of shellfish harvest range from 47.1 to 59.9 million pounds. As shown in Table 4-4, the current annual losses are 30 percent lower than the historic annual losses. The decline in the loss of shellfish harvest due to green crab predation is due to a lower shellfish harvest in recent years compared to the average annual harvest between 1975 and 2005.

Because the green crab is unlikely to spread further on the East Coast, the analysis assumed that there would be no significant change in pounds lost to green crab predation in the future.

Species	Historic Losses (Millions of Pounds)		Current Losses (Millions of Pounds)	
	Total, 1975-2005	Average Annual, 1975-2005	Total, 2001-2005	Average Annual, 2001-2005
Hard-shell clam (quahog)	1,085.4 - 1,227.8	35 - 39.6	148.5 - 185.1	29.7 - 37
Soft-shell clam	500.5 - 550.6	16.1 - 17.8	42.1 - 52.4	8.4 - 10.5
Blue Mussel	391.2 - 492.8	12.6 - 15.9	44.4 - 61.1	8.9 - 12.2
Bay Scallop	115.1 - 115.1	3.7 - 3.7	0.7 - 0.7	0.1 - 0.1
Total	2,092.2 - 2,386.3	67.5 - 77	235.7 - 299.4	47.1 - 59.9

4.3.6 Estimated Historical and Current Commercial Harvest Losses on the West Coast

Table 4-5 shows the estimated current and potential future harvest losses due to green crab predation on West Coast fisheries. Note that while current losses are relatively small, ranging from about 1,200 to 2,300 pounds of shellfish per year, potential future losses are nearly 100 times higher, ranging from 111,200 to 203,600 pounds lost annually.

To estimate the future harvest losses, this analysis first estimates the probability of invasion of bays and estuaries in northern Washington (north of Grey’s Harbor and in Puget Sound) and Alaska. Appendix C presents the estimated probabilities of invasion for the West Coast Estuaries that are currently not infested by green crabs. The expected future harvest losses are then estimated by multiplying the estimated harvest losses by the estimated probability of invasion of a given water body (see Table 4-6). Because the estimated probability of invasion of water bodies north of Grey’s Harbor is very low (0.9 percent) due to abundant populations of Dungeness and red rock crabs, the expected future losses are relatively lower ranging from 111,200 to 203,600 pounds lost annually.

Based on the outer boundaries of the potential green crab spread predicted by GARP (deRivera et al., 2005), this analysis also considered a 100 percent probability of invasion of northern Washington and Alaska. Under this scenario, the estimated loss of commercial shellfish harvest ranges from 1.26 to 2.24 million pounds per year (see Table 4-6) or 10 times higher compared to the estimates presented in Table 4-6.

Table 4-5: Current and Potential Future Annual Harvest Losses by State and Species - West Coast

Species	California (000s of Pounds)		Oregon (000s of Pounds)		Washington ^a (000s of Pounds)		Alaska ^b (000s of Pounds)		West Coast Total (000s of Pounds)	
	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future
Pacific littleneck clam	0 - 0	0 - 0	0* - 0*	0.1 - 0.1	0 - 0	0.2 - 0.2	0 - 0	0.1 - 0.1	0 - 0	0.4 - 0.4
Soft-shell clam	0 - 0	0 - 0	0* - 0*	0* - 0*	0 - 0	0.7 - 1.4	0 - 0	0 - 0	0 - 0	0.7 - 0.7
Manila clam	0.7 - 1.4	2.2 - 4.4	0 - 0	0 - 0	0.3 - 0.5	62.1 - 117.9	0 - 0	0 - 0	1 - 1.9	64.3 - 116.5
Blue mussel	0.2 - 0.4	44 - 84.2	0 - 0	0 - 0	0 - 0	1.8 - 3.4	0 - 0	0 - 0	0.2 - 0.4	46 - 86
Total	1.0 - 1.8	46.2 - 88.6	0 - 0	0.2 - 0.2	0.3 - 0.5	64.8 - 123	0 - 0	0.1 - 0.1	1.2 - 2.3	111.2 - 203.6

* Value between 0 and 0.05
 Puget Sound/Strait of Juan de Fuca losses reduced to account for the 0.9 percent probability of invasion.
 Alaska losses reduced to account for the 0.9 percent probability of invasion.

Table 4-6: Current and Potential Future Annual Harvest Losses by State and Species - West Coast (Assuming 100 Percent Probability of Invasion of Northern Washington and Alaska)

Species	California (000s of Pounds)		Oregon (000s of Pounds)		Washington (000s of Pounds)		Alaska (000s of Pounds)		West Coast Total (000s of Pounds)	
	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future
Pacific littleneck clam	0 - 0	0 - 0	0 - 0*	0.1 - 0.1	0 - 0	16.3 - 26.6	0 - 0	10.1 - 15	0 - 0	26.6 - 41.8
Soft-shell clam	0 - 0	0 - 0	0 - 0*	0 - 0*	0 - 0	76.3 - 146.9	0 - 0	0 - 0	0 - 0	76.3 - 146.9
Manila clam	0.7 - 1.4	2.2 - 4.4	0 - 0	0 - 0	0.3 - 0.5	920.3 - 1596.9	0 - 0	0 - 0	1 - 1.9	922.6 - 1601.3
Blue mussel	0.2 - 0.4	44 - 84.2	0 - 0	0 - 0	0 - 0	191.4 - 368.5	0 - 0	0.2 - 0.4	0.2 - 0.4	235.6 - 453.1
Total	1 - 1.8	46.2 - 88.6	0 - 0	0.2 - 0.2	0.3 - 0.5	1,204.4 - 2,138.9	0 - 0	10.3 - 15.4	1.2 - 2.3	1,261.1 - 2,243.1

*Value between zero and five.

4.4 Economic Impacts on Commercial Shellfishing

4.4.1 Estimating Post-Harvest Economic Surplus in Tiered Markets

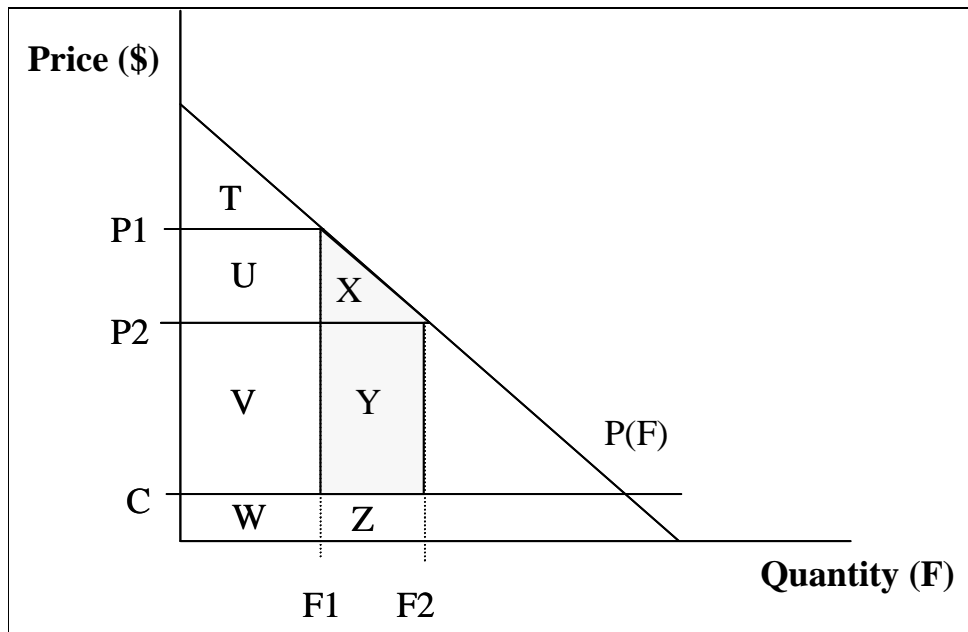
The total loss to the economy from the green crab impacts on commercially harvested shellfish species is determined by the sum of changes in both producer and consumer surplus (Hoagland and Jin, 2006). Producer surplus provides an estimate of the economic damages to commercial shellfishers, but welfare changes can also be expected to accrue to final consumers of fish and to commercial consumers (including processors, wholesalers, retailers, and middlemen) if the projected decrease in catches is accompanied by an increase in price. These impacts can be expected to flow through the tiered commercial fishery market (as described in Holt and Bishop 2002).

This study used a fishery market model to estimate changes in welfare as a result of changes in the level of commercial shellfish harvest. The market model takes as inputs the expected change in harvest and baseline gross revenues, and provides as outputs the expected change in producer and consumer surplus. In general, the analysis of market impacts involves the following steps (Bishop and Holt, 2003):

1. Assessing the net welfare changes for shellfish consumers due to changes in shellfish harvest and the corresponding change in shellfish price.
2. Assessing net welfare changes for shellfish harvesters due to the change in total revenue, which could be positive or negative.
3. Calculating the increase in net social benefits when the shellfish harvest changes.

Exhibit 4-3 illustrates a simplified fishery market model as shown in Bishop and Holt (2003).

Exhibit 4-3: Fishery Market Model



Source: Bishop and Holt (2003).

Step 1: Assessing Benefits to Consumers. The downward sloping line labeled $P(F)$, depicted in Exhibit 4-3, represents a general equilibrium demand function that accounts for markets downstream of harvesters. The curve $F1$ is the quantity of fish supplied to the market by shellfishers under the baseline conditions. Equilibrium is attained at the point where $P(F)$ equals $F1$. The intersection of these two lines gives the price $P1$ at which quantity $F1$ is sold. In this case the total amount paid by consumers for fish is equal to $P1 \times F1$, which is equal to the area of the boxes $U + V + W$ in the graph. The consumer surplus or benefit to consumers is equal to the area of the triangle T .

The measurement of the damages from green crab predation relies on the assumption that a decrease in shellfish mortality in the absence of green crab would increase shellfish populations and the quantity of shellfish supplied to consumers (i.e., an increase from $F1$ to $F2$). If the quantity of fish available to the market increases from $F1$ to $F2$, this in turn would result in a lower market price for shellfish (i.e., $P2$). This changes the total amount paid by consumers to $P2 \times F2$, which is equal to the area of the boxes $V + W + Y + Z$, and increases the consumer surplus so that it is equal to the area of the triangle $T + U + X$. The difference in consumer surplus between the “No Green Crab” and baseline scenarios (i.e., $U + X$) is the measure of damages to consumers from green crab predation.

Estimating the change in price of shellfish from changes in commercial shellfish harvest requires the following input data: (1) the estimated change in the commercial shellfish harvest in the absence of green crab predation and (2) an understanding of the price elasticity of demand for shellfish. Section 4.3 describes methods and data used in estimating shellfish harvest losses due to green crab predation. The price elasticity of demand for shellfish measures the percentage change in demand in response to a percentage change in shellfish price. EPA's review of the economics literature identified several potentially relevant studies, including Lipton and Strand (1992), Cheng and Capps (1988), and Lambregts (1991).²⁰ This review revealed that the price elasticity may differ significantly across species and regional markets. Because green crab predation affects a variety of shellfish species on both the East and West Coasts of the United States, we selected an estimate of the elasticity of demand for all shellfish in the United States from Cheng and Capps (1988). Cheng and Capps estimated that the demand for shellfish is slightly inelastic, with an own-price elasticity of -0.885 .

Step 2: Assessing Producer Surplus. In an unregulated fishery, the long-run change in producer surplus due to an increase in shellfish stock will be zero percent of the change in gross revenues. Most shellfisheries are, however, regulated with quotas or restrictive permits. Thus, there will be lasting economic damages to commercial shellfish harvesters from green crab predation. Fishery regulations seek to create sustainable harvests that maximize resource rents. In a regulated fishery, green crab impacts reduce the number of shellfish available to harvest. This may lead to more stringent regulations and decreases in harvest. In this case, the change in producer surplus can be related to the change in quota and the resulting gross revenue.

In Exhibit 4-3, the line C represents a simplified representation of the cost to the producer of supplying a pound of fish. For this analysis, C is assumed to be constant, for all units of F produced.²¹ When the supply of fish is equal to $F1$, the shellfish producers sell $F1$ pounds of fish at a price of $P1$ and earn revenues equal to $U + V + W$. The difference between $P1$ and C is the producer surplus that accrues to producers for each pound of shellfish. Total producer surplus realized by producers is equal to $(P1 - C) \times F1$. In the example, this producer surplus is equal to the area of $U + V$. The area W is the amount that producers pay to their suppliers if the harvest equals $F1$ (e.g., fishing gear and the costs of operating the market).

When supply increases to $F2$, the producers sell $F2$ pounds of fish at a price of $P2$. The total cost to produce $F2$ increases from W to $W + Z$. The total producer surplus changes from $U + V$ to $V + Y$. This change may be either positive or negative, depending on the relative elasticity of demand.

In theory, producer surplus (net benefit) is equal to normal profits (total revenue minus fixed and variable costs), minus the opportunity cost of capital. The fixed costs and inputs are incurred independently of the expected marginal changes in the level of shellfish landings (Tsongburg and Squires, 2005; Squires 1998). Variable costs such as labor, fuel, ice, and other supplies, however, vary directly with the level of landings. Furthermore, since the opportunity cost of capital is estimated to be only about 0.4 to 2.6 percent of producer surplus, normal profits are assumed a sufficient proxy for producer surplus (U.S. EPA, 2004). As a result, assessment of producer surplus is reduced to a relatively straightforward calculation in which the change in producer

²⁰ This review was originally conducted to support benefits analysis of the final regulations for concentrated animal feeding operations (Griffiths and Lovell 2002). Additional review of economic literature did not yield more recent studies of demand for shellfish.

²¹ If marginal cost increases as harvest increases, some of the producer surplus per unit will be eaten away by increased costs.

surplus is calculated as a species- and region-specific fraction of the change in gross revenue due to increased landings.

To analyze changes in producer surplus, EPA obtained information on the variable costs incurred by the shellfish industry as a proportion of its revenues by modifying the production functions estimated by Steinbeck and Thunberg (2006) for the Northeast Region Commercial Fishing Input-Output Model. The estimated net benefit ratio for wild shellfish harvesters is 0.58. Data on the variable costs associated with aquaculture production were obtained from the Economic Activity Associated with Clam Aquaculture in Virginia – 2004 study (Murray and Kirkley, 2005). The estimated net benefit ratio for aquaculture producers is 0.5.

Step 3: Estimating Net Social Benefits When the Shellfish Harvest Increases. The change in net social benefits when the shellfish harvest increases from $F1$ to $F2$ is estimated by adding the results from Steps 1 and 2. Because area U is a transfer from shellfish harvesters to consumers, it does not result in an increase in social benefits. Therefore, the change in net social benefits is area $X + Y$.

We note that Exhibit 4-3 is a graphical representation of a single market. In the real world, a shellfish producer sells his harvest to shellfish wholesalers, who in turn sells shellfish to retailers or restaurants, which sell shellfish to consumers. There will be consumer and producer surplus in each of these markets.

4.4.2 Results

As shown in Table 4-7, the estimated annual losses to shellfisheries on the East Coast due to green crab predation range from \$14.7 to \$18.7 million. The estimated total historic losses on the East Coast during 1975–2005 range from \$719.1 to \$805.9 million. All monetary values are in 2006 dollars.

Table 4-7: Value of Historic and Current Harvest Losses – East Coast (Annual Consumer and Producer Surplus Lost)				
Species	Historic Losses (Millions of Dollars)		Current Losses (Millions of Dollars)	
	Average Annual, 1975–2005	Total, 1975–2005	Average Annual, 2001–2005	Total, 2001–2005
Hard-shell clam (quahog)	\$13.9 - \$15.7	\$431.5 - \$486.9	\$9 - \$11.4	\$45.1 - \$56.8
Soft-shell clam	\$6.5 - \$7.3	\$202.8 - \$227.1	\$4.8 - \$6.1	\$23.9 - \$30.4
Blue mussel	\$0.8 - \$1	\$25 - \$32.1	\$0.8 - \$1.1	\$3.9 - \$5.6
Bay scallop	\$1.9 - \$1.9	\$59.7 - \$59.7	\$0.1 - \$0.1	\$0.5 - \$0.5
Total	\$23.2 - \$26	\$719.1 - \$805.9	\$14.7 - \$18.7	\$73.5 - \$93.4

Table 4-8 presents estimates of current and potential annual losses of harvestable shellfish on the West Coast. Although the estimated current losses to shellfisheries on the West Coast are negligible, the potential future losses are likely to increase to up to \$82,000 per year. The total present value of potential commercial harvest losses due to green crab predation over 25 years is \$1.6 million. All monetary values are in 2006 dollars; the annualized and present values were estimated using a 3 percent discount rate.

Table 4-8: Value of Current Annual and Potential Future Harvest Losses by State and Species - West Coast

Species	California (Thousands of 2006\$)		Oregon (Thousands of 2006\$)		Washington (Thousands of 2006\$)		Alaska (Thousands of 2006\$)		West Coast Total (Thousands of 2006\$)	
	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future
Pac. littleneck clam	\$0-\$0	\$0-\$0	\$0*-\$0*	\$0.1-\$0.1	\$0-\$0	\$0.1-\$0.1	\$0-\$0	\$0.1-\$0.1	\$0-\$0	\$0.2-\$0.3
Soft-shell clam	\$0-\$0	\$0-\$0	\$0*-\$0*	\$0*-\$0*	\$0-\$0	\$0.1-\$0.2	\$0-\$0	\$0-\$0	\$0-\$0	\$0.1-\$0.2
Manila clam	\$0.4-\$0.8	\$1.2-\$2.8	\$0-\$0	\$0-\$0.1	\$0.1-\$0.3	\$25.4-\$48.2	\$0-\$0	\$0-\$0	\$0.6-\$1.1	\$26.6-\$51.1
Blue mussel	\$0.1-\$0.2	\$14.8-\$29	\$0-\$0	\$0-\$0.1	\$0-\$0	\$0.7-\$1.4	\$0-\$0	\$0-\$0	\$0.1-\$0.2	\$15.5-\$30.6
Total	\$0.5-\$1	\$16-\$31.8	\$0-\$0	\$0.2-\$0.3	\$0.1-\$0.3	\$26.2-\$49.9	\$0-\$0	\$0.1-\$0.1	\$0.7-\$1.3	\$42.5-\$82.2

* Value greater than \$0, but less than \$50.

If a 100 percent probability of green crab invasion of water bodies in northern Washington and Alaska is assumed, the potential future losses on the West Coast will range from \$0.58 to \$1.14 million annually. Table 4-9 presents estimates of current and potential annual losses of harvestable shellfish on the West Coast assuming a 100 percent probability of green crab invasion in northern Washington and Alaska. The total present value of potential commercial harvest losses due to green crab predation over 25 years is \$21.8 million. All monetary values are in 2006 dollars; the annualized and present values were estimated using a 3 percent discount rate.

Table 4-9: Value of Current Annual and Potential Future Harvest Losses by State and Species - West Coast (Assuming 100 Percent Probability of Invasion of Northern Washington and Alaska)

Species	California (Thousands of 2006\$)		Oregon (Thousands of 2006\$)		Washington (Thousands of 2006\$)		Alaska (Thousands of 2006\$)		West Coast Total (Thousands of 2006\$)	
	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future	Current	Potential Future
Pac. littleneck clam	0 - 0	2.4 - 6	0 - 0*	0.3 - 0.7	0 - 0	9.9 - 16.3	0 - 0	6.1 - 8.9	0 - 0	18.8 - 31.9
Soft-shell clam	0 - 0	1.5 - 5.7	0 - 0*	0.2 - 0.6	0 - 0	12 - 23.5	0 - 0	0 - 0.1	0 - 0	13.7 - 29.9
Manila clam	0.4 - 0.8	56.4 - 169	0 - 0	5.6 - 17	0.1 - 0.3	396.9 - 691.6	0 - 0	1 - 3.1	0.6 - 1.1	460.0 - 880.6
Blue mussel	0.1 - 0.2	24.6 - 65.3	0 - 0	1 - 3.8	0 - 0	64.6 - 127.5	0 - 0	0.3 - 0.8	0.1 - 0.2	90.5 - 197.4
Total	0.5 - 1	85 - 245.9	0 - 0	7.2 - 22.1	0.1 - 0.3	483.4 - 858.9	0 - 0	7.4 - 12.9	0.7 - 1.3	583.0 - 1139.7

* Value greater than \$0, but less than \$50

4.5 Limitations and Uncertainty

This section summarizes the caveats, omissions, biases, and uncertainties known to affect the estimates that were developed for the analysis of economic damages from green crab predation to commercial shellfishers and consumers.

1. As described in Section 4.2, the estimated predation function is based on limited data. It is unclear whether these data limitations have a significant effect on parameter estimates, and, as a result, would lead to an upward or downward bias in estimated values.
2. EPA assumed a linear stock-to-harvest relationship, so that a 20 percent change in shellfish population would result in a 20 percent change in shellfish harvest; this may either over- or underestimate changes in harvest, depending on the condition of the stocks. State-specific regulations will also affect the validity of the linear assumption.
3. EPA assumes that shellfish harvest data provided by NOAA and states are accurate and complete. In some cases prices and/or quantities may be reported incorrectly.
4. This analysis does not include all commercially harvested species potentially affected by green crab predation due to data availability (e.g., oysters) or time constraints (e.g., winter flounder).
5. The analysis relies on estimates of the price elasticity of demand for shellfish from a 1988 study. Given that the study was conducted almost 20 years ago, the price elasticity of demand for shellfish reported by Cheng and Capps may not be representative of current market conditions. It is unclear whether it would lead to an upward or downward bias in estimated values.
6. Many commercial fishery markets do not adhere to the usual assumptions of the neoclassical model because of regulations that establish harvest quotas and/or restrict entry through a permit system. Although there are positive rents accruing from the fishery resource in regulated markets (or a non-regulated market with economic barriers to entry), the exact impact of fishery regulations on rents are difficult to estimate. Therefore, the estimated changes in producer surplus from green crab predation are subject to uncertainty.
7. Empirical evidence regarding the absolute magnitude of producer surplus is limited (especially for inferring a relationship with gross revenues). The proxy used in this analysis is based on a ratio between normal profits and gross revenue and is called the net benefits ratio (NBRatio). Available empirical data pertain to average producer surplus, while the analysis of commercial impacts from green crab predation must instead address changes in producer surplus at the margin.

5. Economic Impacts on Recreational Shellfishing

Shellfish species such as the soft-shell clam, hard-shell clam, the blue mussel, Manila clam, scallops, and oysters that are harvested commercially are also harvested by recreational users and beachgoers. Recreational shellfishing is a significant contributor to local economies in many coastal counties and states on both the East and West Coasts of the United States (Damery and Allen, 2004). A reduction in the number of available recreational species could correspond to a reduction in the number of organisms caught and the associated marginal decreases in utility experienced by individuals participating in these activities. The magnitude of the green crab's impact on recreational shellfishing could be evaluated using a non-market valuation approach. Stated or revealed preference methods, or benefit transfers based on these studies, are the generally accepted techniques for estimating recreational use values. Because EPA did not have sufficient time to conduct an original stated or revealed preference study to estimate the non-

market value of green crab impacts, benefit transfer was the only remaining option for providing information to inform policy decisions.

Inputs required for analyzing damages to recreational users from green crab predation include estimates of green crab density in the affected areas, the type of species affected, changes in recreational shellfish harvest, and the economic value of changes in recreational shellfish harvest from prior studies.

Analyzing the economic value of green crab impacts on recreational shellfishing is, however, challenging due to the scarcity of information on the value of shellfishing and the incremental change in this value due to changes in shellfish harvest. Although there are several economic studies of recreational shellfishing values in the literature, the majority of the available studies do not provide a very good match to the policy scenarios considered in this analysis. Only one study (Damery and Allen, 2004) allows estimating the incremental change in recreational shellfishing value due to changes in shellfish harvest. Thus, the analysis of green crab impacts on recreational shellfishing presented in this section relies on benefit function transfer from Damery and Allen (2004).

5.1 Shellfish Valuation Studies

Our literature search yielded a limited number of shellfish valuation papers. Moreover, most of these studies do not value shellfishing directly but rather estimate willingness to pay (WTP) for improvements in water quality that would ensure year-round shellfishing in the study areas (Hayes et al., 1992; Kaoru, 1993; Wey, 1990). There are also a number of studies that elicit WTP for preserving habitats essential for supporting fish and shellfish species, including wetlands and eelgrass (Woodward and Wui, 2001; Johnston et al., 2001; Opaluch et al., 1998; Mazzotta, 1996; Anderson and Rockel, 1991). A few relevant examples are provided below.

Three studies provide estimates of WTP for improving water quality to levels safe for shellfishing. A study by Hayes et al. (1992) uses a discrete choice valuation survey to estimate WTP (including option and existence values) for an improvement in water quality such that shellfishing in the upper Narragansett Bay in Rhode Island can occur unconditionally. Mean annual WTP for improving water quality to levels safe for shellfishing ranged from \$37.2 to \$71.1 million (1984\$), depending on question formulation. A 1993 study by Kaoru estimates per-household WTP for water quality improvements of three coastal ponds on Martha's Vineyard, Massachusetts, that would allow shellfishing year-round. The estimated mean WTP to raise water quality to allow year-round shellfishing was \$131.03 per household per year. The use-only value amounted to \$33.69 per household per year, the existence value (bequest value) to \$77.59 per household per year, and the option-use only value to \$19.41 per household per year (all values in 1993\$). Finally, a stated preference study by Wey (1990) estimates WTP for water quality improvements in the Great Salt Pond on Block Island, Rhode Island, that would allow shellfishing. The estimated annual WTP for water quality improvements to a level safe enough for shellfishing are \$55.60 and \$200.25 (2003\$) to Block Island residents and visiting boaters, respectively.

In addition, there are several economic studies of recreational shellfishing values in the literature. For example, the total recreational values of shellfishing are available for Long Island Sound, Puget Sound, and Cape Cod (Damery and Allen, 2004). However, only one study (Damery and Allen, 2004) allows estimating the incremental change in recreational shellfishing value due to changes in shellfish harvest. Damery and Allen (2004) estimate the total value of shellfishing on Cape Cod based on the actual permit fee and the estimated consumer surplus. Consumer surplus

was estimated using two payment estimation techniques: (1) willingness to accept (WTA) compensation to give up a shellfishing permit and (2) willingness to pay to purchase a permit. The estimated total value of recreational shellfishing was \$7.4 and \$1.0 million in 2002 based on the WTA and WTP estimates, respectively. The study found that individuals' valuation of recreational shellfishing depends on several factors, including travel distance, the number of trips in the prior year, the number of years a permit was held, and the total annual quahog harvest. The study also provides estimates of the total catch of targeted shellfish species, including quahog, soft-shell clams, oysters, and mussels, by respondent.

5.2 Data and Method

The analysis of economic impacts on recreational users relies on benefit function transfer from Damery and Allen (2004) in conjunction with information on the change in recreational harvest loss due green crab predation. This analysis involves the following general steps:

1. Assessing changes in recreational shellfish harvest due to green crab predation
2. Estimating changes in WTP for a shellfishing permit due to changes in shellfish harvest
3. Estimating the number of recreational shellfish users
4. Estimating the total value of changes in shellfish harvest from green crab predation to recreational users.

Due to data limitations, this analysis focuses on recreational harvest of the hard-shell clam, *Mercenaria mercenaria*, only and is limited to seven East Coast states: Connecticut, Delaware, Maine, Massachusetts, New Jersey, New York, and Rhode Island.

5.2.1 Assessing Recreational Harvest Losses

This study estimates green crab impacts on recreational shellfish harvest using the damage function discussed in Section 4.2, green crab density ranges presented in Section 4.3, and data on recreational shellfish landings of species addressed in this analysis. The recreational impact analysis uses the same ecological damage function, based on green crab density, as is used to estimate the impact of green crabs on commercial shellfisheries. The output of this analysis is the percentage change in harvest in the presence and absence of green crabs for each state. The estimated percentage change is then used to scale the quahog harvest parameter in the Damery and Allen (2004) WTP function.

Recreational harvest data on the hard-shell clam, *Mercenaria mercenaria*, were available for the years 1995 to 2004 from two states: Delaware and Massachusetts. These data were obtained from the following sources:

1. Recreational harvested data collected by the Massachusetts Division of Marine Fisheries (Churchill, 2007)
2. The 2004 Delaware Recreational Hard Clam Harvest and Effort Survey Using a License Frame, Delaware Division of Fish and Wildlife (Whitmore, 2005).

Data on recreational shellfish harvest for other East Coast states were not available. Thus, this study uses a ratio of recreational to wild-caught commercial harvest for the state of Delaware to estimate recreational shellfishing for the remaining five East Coast states. We calculated the ratio using fishing data from Delaware only because recreational data for this state, from 1995 to 2004, were most complete. The ratio of recreational to wild-caught commercial shellfish harvest used in this analysis is 6. We used the value of wild-caught commercial harvest because recreational

harvest depends on the same wild stock, making for a consistent ratio. The estimated ratio was then applied to wild-caught commercial harvest values reported for the five states by NOAA’s National Marine Fisheries Service²² to estimate the recreational shellfish harvest for the remaining five East Coast states. Table 5-4 in Section 5.3 presents estimated recreational harvest by state. The estimated total recreational shellfish harvest in the six East Coast states is 169.2 million pounds per year.

5.2.2 Estimating Changes in WTP for a Shellfishing Permit

This study uses the WTP function from Damery and Allen (2004) to estimate state-specific WTP for a shellfishing permit in the seven East Coast states. Table 5-1 summarizes the estimated regression coefficients from Damery and Allen (2004). Although regression results reveal systematic elements influencing WTP for a shellfishing permit, the model as a whole is relatively weak. The adjusted R-square is 0.30. Of the six independent variables in the model (not including the intercept), four (annual quahog harvest, trips per year, permit fee paid in 2002, and household income) are statistically significant at the 5 percent level. Two variables (distance traveled to flats, and years purchasing permits) were found not to be significant. Signs of significant parameter estimates generally correspond with intuition, where prior expectations exist. Of particular importance is the positive and statistically significant ($p < 0.05$) coefficient on the annual quahog harvest variable. This finding indicates that gains in shellfish populations or harvests are associated with statistically significant increases in WTP for a shellfish permit. Therefore, the model allows estimating WTP for marginal improvements in shellfish harvest.

Variable	Regression Coefficient	Standard Deviation	P-Value
Constant	0.4684	0.5596	0.404
Distance traveled	0.0176	0.0674	0.795
Annual quahog harvest	0.1544	0.0783	0.051
Trips per year	0.1908	0.0928	0.042
Years purchasing permits	0.0317	0.0603	0.6
Permit fee paid in 2002	0.3967	0.0797	<. 0001
Household income	0.3283	0.101	0.002

Source: Damery and Allen, 2004.
Notes: R² = .301, n = 135

Damery and Allen (2004) report that parameter estimates did not vary significantly across residency type (i.e., residents, non-residents, and senior permit holders). Thus, EPA uses the same parameter estimates for analyzing welfare changes to resident and non-resident shellfish users.

To estimate WTP for a shellfishing permit under different analytic scenarios (i.e., current conditions and the absence of green crabs), we assigned values to independent variables to reflect state- and scenario-specific resource characteristics, area demographics, and other factors (see Table 5-2).

²² This method assumes that the ratio of recreational to commercial harvest is the same for all East Coast states included in this analysis.

Table 5-2: Values of Independent Regressors in the WTP Function	
Variable Name	Value Assignment and Explanation
Constant	Set to one because a constant was included in the WTP function.
Distance traveled	Set to an average distance traveled to shellfish beds (5 miles) as reported in Damery and Allen (2004).
Annual quahog harvest (in pounds)	The baseline value is set to an average annual harvest (130 pounds) reported in Damery and Allen (2004). Under the “No Green Crab” scenario, we adjusted this value based on the estimated percentage change in recreational shellfish due to eliminating shellfish losses from green crab predation.
Trips per year	Set to an average number of shellfish trips per year (11.7) as reported in Damery and Allen (2004).
Years purchasing permits	Set to an average number of years of purchasing a permit (15) as reported in Damery and Allen (2004).
Permit fee paid in 2006	Varies by state and is based on an average of quahog-specific permits or shellfishing permits for residents and non-residents, where data were available.
Household income	EPA assigned state-specific values to this variable based on average household income data from the 2002 Census of Population and Housing (U.S. Census Bureau, 2002).

In this analysis, the values of variables characterizing recreational shellfish users (years purchasing permits, trips per year, and distance traveled) are the same for all East Coast states. The values for these variables are set to the respective averages reported in Damery and Allen (2004). The analysis also assumes that per capita quahog harvest in all seven states is the same as the average value reported in the Damery and Allen (2004) under the current conditions. The value assignments of the quahog harvest variable under the “No Green Crab” scenario are based on the expected change in recreational shellfish harvest estimated in the previous step. Finally, we used state-specific data to assign values to the permit fee and household income variables. Permit fees range from \$10 to \$18.83 for residential users and from \$34.92 to \$200 for non-residential users. Recreational shellfishing permits are not required for resident shellfishers in Rhode Island and for non-resident shellfishers in New York. Appendix B provides state-specific values for permit fee and household income.

To predict the average WTP for a shellfishing permit for a user in a given East Coast state, we multiplied the independent variable values by the estimated regression coefficients. Table 5-3 presents the estimated WTP for a shellfishing permit by state and analytic scenario. The difference in WTP for a shellfishing permit between the baseline and “No Green Crab” scenarios is the economic damage to recreational shellfishers from green crab predation. The estimated annual welfare loss to a resident shellfisher ranges from \$2.44 to \$3.67. The estimated annual welfare loss to a non-resident shellfisher ranges from \$4.09 to \$9.63 (2006\$).

5.2.3 Estimating the Total Welfare Loss to Recreational Users

Welfare loss by state was estimated by multiplying the change in WTP based on foregone harvest due to green crab predation as described above by the number of shellfishing permits issued by each state. However, data on recreational shellfishing permits sold by state are not readily available. Therefore, we approximated the number of recreational shellfish users based on the average annual harvest per user and the total recreational shellfish harvest in a given state. This analysis assumes that the average harvest reported by the Damery and Allen (2004) survey

respondents, 2.6 bushels (130 pounds) per user per year, is representative of recreational shellfishers in the seven East Coast states included in this analysis. We therefore divided recreational harvest by 130 pounds to obtain the total number of permit holders. The estimated number of permit holders by state is as follows: Connecticut (115,886); Delaware (3,747); Massachusetts (13,415); Maine (837); New Jersey (71,589); and New York (93,192); and Rhode Island (5,854).²³ We then multiplied the estimated number of shellfishing permit holders in a given state by the estimated change in WTP due to reduction in recreational shellfish harvest from green crab predation to obtain welfare loss by state due to green crab predation.

State	Residents			Non-residents		
	Baseline	No Green Crab	Change	Baseline	No Green Crab	Change
Connecticut	\$42.74	\$46.41	\$3.67	\$59.55	\$64.65	\$5.11
Delaware	\$28.38	\$30.82	\$2.44	\$70.75	\$76.83	\$6.08
Maine	\$41.19	\$44.73	\$3.54	\$52.90	\$57.79	\$4.89
Massachusetts	\$42.51	\$46.16	\$3.65	\$71.60	\$77.75	\$6.15
New Jersey	\$36.22	\$39.33	\$3.10	\$47.69	\$51.77	\$4.09
New York	\$33.63	\$36.52	\$2.89	N/A	N/A	N/A
Rhode Island	N/A	N/A	N/A	\$112.16	\$121.80	\$9.63

Note: N/A indicates that a shellfishing permit was not required.

5.3 Results

Table 5-4 summarizes the estimated average annual losses to the recreational shellfish harvest due to green crab predation for the seven East Coast states included in this analysis. The total annual loss in shellfish harvest due to green crab predation, for all seven states, is 119.3 million pounds. The total welfare loss to the East Coast recreational users is \$3.8 million per year.

State	Total Current Harvest, Whole Weight (000 lbs)	Estimated Losses from Green Crab Predation, Whole Weight (000 lbs)	Total Welfare Loss from Reduction in Quahog Harvest (000 2006\$)
Connecticut	58,569	41,035	\$1,729
Delaware	487	343	\$11
Maine	423	303	\$12
Massachusetts	109	78	\$53
New Jersey	36,181	25,526	\$897
New York	47,100	33,376	\$921
Rhode Island	24,655	17,401	\$219
Total	169,160	119,276	\$3,842

Note: All harvest and loss values reflect averaged values from 1995 to 2004 where data were available. Current harvest data were not available for all years for Maine (1995, 1996) and New Jersey (2002).

²³ The total number of shellfishing permits sold in Rhode Island includes non-residents only because residents are not required to buy a permit.

5.4 Limitations and Uncertainties

A number of issues are common to all benefit transfers. Benefit transfer involves adapting research conducted for another purpose in the available literature to address the policy questions at hand. Benefit transfers are by definition characterized by a difference between the context in which resource values are estimated and that in which benefit estimates are desired. The ability of benefit function transfer to adjust for the influence of resource and demographic characteristics on WTP can reduce, but not eliminate potential biases. The WTP function used in EPA's analysis provide a close, but not perfect, match to the context in which values are desired. Some of the key limitations inherent to benefit transfer are the following:

1. Limitations associated with the WTP function estimated by Damery and Allen (2004):
 - a. WTP for a shellfish permit is estimated as a function of the annual quahog harvest. This study, however, calls for WTP for a shellfish permit as a function of harvest of multiple shellfish species, including hard-shell clam, soft-shell clam, blue mussels, and scallops. If harvest of other shellfish species (e.g., soft-shell clam) has a significant influence on WTP for a shellfish permit, the total value of damages from green crab predation is likely to be underestimated.
 - b. As noted in Damery and Allen (2004), the explanatory power of the estimated WTP model is relatively "weak." If the model omits other variables that significantly influence WTP for a shellfish permit, the estimated coefficient on the quahog harvest is likely to be biased. It is unclear whether this will lead to an upward or downward bias in estimated values.
 - c. The study is limited to one location — Cape Cod. The extent to which shellfishers and their trip characteristics (e.g., number of trips per year, distance traveled to flats, years purchasing permits, and annual quahog harvest) differ across East Coast states will influence the validity of benefit transfer results. It is unclear whether these potential limitations, if indeed significant, will lead to an upward or downward bias in estimated values.
 - d. Because the Damery and Allen (2004) study was conducted on the East Coast and limited to the hard-shell clam (*Mercenaria mercenaria*), which is not harvested on the West Coast, we deemed this study not applicable to the West Coast analysis. Thus, the estimated welfare losses to recreational users from green crab predation are limited to the East Coast states only.
2. Complete recreational harvest data on the hard-shell clam, *Mercenaria mercenaria*, were available from Delaware only. As noted in Section 5.2.1, we used the estimated ratio of recreational to commercial shellfish harvest for Delaware in conjunction with the state-level data on commercial quahog harvest to approximate recreational harvest in the remaining five East Coast states. If the ratio of recreational to commercial wild-caught harvest were different across the East Coast states, this approximation would lead to an upward or downward bias in the estimated values.
3. Because data on the number of shellfish permit holders in each state were not readily available, we estimated the number of recreational shellfishers in each state based on the total annual quahog harvest in a given state and the average annual quahog harvest per shellfisher reported in Damery and Allen (2004). Because per-shellfisher harvest may differ from one location to another, the estimated number of permit holders in each state is an approximation. It is unclear whether this approximation would lead to an upward or downward bias in estimated values.

4. Estimates of shellfish losses from green crab predation are only for individuals directly lost to green crabs and not for their progeny.

Additional limitations and uncertainties associated with estimation of ecological damages from green crab predation are addressed in Section 4.4.

We also note that in addition to use values such as those associated with recreational and commercial shellfishing, both users and nonusers of shellfishery resources may hold values that are independent of any current or anticipated uses of the resource (non-use values). The non-use values are not included in this analysis.

6. Eelgrass Damages

As discussed in Section 3.1.1, as green crabs forage for food, they sometimes cut or tear through eelgrass shoots' sheath bundles. Because the majority of available data deal with the green crabs' potential to interfere with eelgrass restoration efforts rather than with the crabs' impacts on healthy eelgrass beds, this study estimates the monetary value of damages to restoration projects. To do so, this study uses approximate estimates of the degree of damage a particular density of green crabs might produce in conjunction with the value of ongoing eelgrass restoration projects. We note that at present we only have approximate estimates of damage from field restoration plots as well as estimates based on laboratory or mesocosm experiments, which have the potential to overestimate this kind of damage; therefore, cost estimates will be approximate. Furthermore, because of a lack of comprehensive data on eelgrass restoration projects on either coast, this analysis estimates damages and eelgrass replacement values for a "typical" project on each coast, rather than for all projects.

6.1 Eelgrass Damage Function

To model the impact of crab abundance on eelgrass damage, this study uses the Type III functional form to represent predator-prey interactions because it has the best fit (R-square). Data for density-based impacts of green crabs are taken from Davis et al. (1998).

To model green crab impacts on eelgrass restoration we used the following functional form:

$$\text{Eelgrass Losses} = \frac{b_0 * \text{Crab Density}^{b_2}}{b_1^{b_2} + \text{Crab Density}^{b_2}} \quad (5)$$

Where b_0 , b_1 and b_2 are the parameters of the functional form that determine the shape of the sigmoid function. Parameter estimates are shown in Table 6-1. This function reflects the asymptotic relationship between green crab density and eelgrass losses seen in Davis et al. (1998), likely due to interference interactions among green crabs at the highest densities.

Table 6-1: Impacts of Green Crab Bioturbation on Eelgrass Restoration			
Dependent Variable: Percentage Loss of Eelgrass			
Independent Variable: Green Crab Densities			
Parameter	Parameter Estimate	Standard Error	t-statistic
b_0	0.40	2.65	0.15
b_1	61.6	2699.8	0.02
b_2	0.32	2.74	0.12
Number of Observations: 6			
R-Square: 0.81			
Adjusted R-Square 0.61			
F(3, 3) = 4.14, Prob >f = 0.1368			
Non-linear estimation. Standard errors are asymptotic approximations.			

6.2 Restoration Project Data and Method

The eelgrass damage function presented in Section 6.1 provides the percentage of acres involved in a restoration project that could be lost to green crab bioturbation at a given crab population density. This study estimated a range of potential losses based on the low, high, and midpoint green crab densities observed on each coast. The density values (all in crabs per trap per day) used were as follows (See Appendix A for data sources):

- East Coast – Low: 27.4; Midpoint: 76.2; and High: 133.15²⁴
- West Coast – Low: 0.01; Midpoint: 15.755; and High: 31.15.²⁵

The estimated percentage of acres lost was applied to the size of a typical restoration project on each coast (see Sections 6.2.1 and 6.2.2 below), and the number of lost acres was then multiplied by the average cost of replacing an acre of eelgrass to calculate the value of damages caused by *C. maenas*.

6.2.1 West Coast

Of the West Coast states affected by green crab predation, only California has readily available documentation of eelgrass restoration projects. This study relies on data for the 41 recorded eelgrass restoration efforts undertaken in California between 1976 and 1999 (Thom et al., 2001). Based on the most recent 13 projects reported by Thom et al., this study estimates that the average size of a restoration project in California is 2.85 acres.²⁶ The cost of restoring an acre of California eelgrass is approximately \$35,417 (Boyer, 2007).

6.2.2 East Coast

For the East Coast analysis, we obtained data on restoration project size thorough queries of federal and state databases (e.g., EPA's Restoration Project Directory, Coastal America.com's Regional Conservation Projects). These queries returned 11 eelgrass restoration projects undertaken since 2001 in the East Coast states invaded by the European green crab. Based on these data, each restoration project involved about 6.97 acres of eelgrass. The cost of restoring an acre of eelgrass on the East Coast is \$49,382 (Leschen, 2007).

²⁴ The low and high density values correspond to the 1st and 3rd quartile values reported in Table A-1 (see Appendix A).

²⁵ Density data included a single outlier of 72.33 CPUE, which was dropped from the calculations.

²⁶ The 13 projects included in this calculation took place between 1995 and 1999 and restored a total of 15 ha, or 37 acres, of eelgrass.

6.3 Results

Table 6-2 summarizes the results of this analysis. The estimated losses to eelgrass restoration projects range from 2.3 to 18 percent of acres involved in a given project on the West Coast and between 17.5 and 22.5 percent on the East Coast. The estimated value of potential green crab damages per restoration project ranges from \$2,366 to \$18,084 (2006\$) on the West Coast and from \$60,150 to \$77,433 (2006\$) on the East Coast.²⁷

Table 6-2: Estimated Damages to Eelgrass Restoration Projects from Green Crab Bioturbation (2006\$)					
Green Crab Density (CPUE)	Estimated Acres	Eelgrass Lost (%)	Eelgrass Lost (Acres)	Cost/Acre Eelgrass Transplant	Cost of Replacing Eelgrass
California^a					
Low (.01)	2.85	2.34%	0.07	\$35,417	\$2,366
Midpoint (15.755)	2.85	15.76%	0.45	\$35,417	\$15,911
High (31.5)	2.85	17.91%	0.51	\$35,417	\$18,084
East Coast^b					
Low (27.40)	6.97	17.47%	1.22	\$49,382	\$60,150
Mean (76.20)	6.97	20.72%	1.44	\$49,382	\$71,341
High (133.15)	6.97	22.49%	1.57	\$49,382	\$77,433
<small>^a California Sources: Davis et al., 1998; Independent Sector, 2007; Boyer, 2007; and U.S. Department of Labor, 2007. ^b East Coast Sources: Independent Sector, 2007; Leschen, 2007; U.S. Department of Labor, 2007; Trowbridge, 2003; Massachusetts Division of Marine Fisheries, 2006; Tuxbury, 2007; SeagrassLI, 2007; and U.S. EPA, 2002a,b.</small>					

7. Invasion Management and Control Strategies

In 2002, the Green Crab Control Committee submitted a management plan for *C. maenas* to the Aquatic Nuisance Species Task Force. The management plan identifies steps that can be taken to prevent, halt, and mitigate green crab invasions and recommends the establishment of an information network to allow for rapid communication between organizations involved in prevention and control activities. The plan incorporates response strategies at all stages of an invasion, from prevention of new introductions, to mitigation where eradication or even control of the green crab population is no longer possible. In this section, we summarize potential green crab invasion prevention and control strategies, following the Green Crab Control Committee's management plan model, and discuss the viability of these strategies.

7.1 Prevention and Containment

When feasible, the prevention of future introductions is perhaps the best approach to invasion control. According to the Green Crab Control Committee, the prevention and containment step should involve a risk analysis of potential human-mediated introduction pathways. This analysis should be used to "identify points along the pathways where interventions can effectively reduce the risk of new invasions." Industry contacts and education programs should be developed and

²⁷ We note that this analysis does not consider social benefits of eelgrass restoration. The estimated damages are expressed in terms of lost expenditures on restoration projects due to green crab predation.

implemented to increase awareness of the risks posed by particular human activities, such as near-shore exchange of ballast water or the shipment of aquaculture products.

For example, Washington State is an aggressive user of preventive strategies. After green crabs first appeared in Willapa Bay and Gray Harbor, the Washington Department of Fish and Wildlife established restrictions on the transfer of shellfish and aquaculture into and within Washington state (Holmes, 2001). Shellfish seed and broodstock imported from crab-infested areas outside of Washington are subject to 1-hour chlorine dips; the transfer of shellfish or aquaculture from Willapa Bay or Gray's Harbor to other Washington waters is generally prohibited. Emergency regulation WAC 232-12-01701 requires a special permit for the possession or transportation of live green crabs. In addition, in the spring of 2000, the state promulgated the Ballast Water Management Act, which requires vessels to "exchange ballast water at least 50 miles offshore and report the exchange" (Holmes, 2001). The discharge of unexchanged ballast water into Washington waters is prohibited. As of 2001, the only other state with similar regulations was California (Holmes, 2001).²⁸ It is likely that these preventive strategies have helped to restrict green crab populations in Washington to the two water bodies where they first appeared in 1998.

7.2 Detection and Forecasting

As discussed in Section 2.3.2, in addition to human-mediated pathways, green crabs are likely to disperse over short distances (i.e., along the coast) via natural vectors such as ocean currents. As such, while prevention and containment strategies are useful in avoiding human-mediated introductions, continuous monitoring of at-risk water bodies is also necessary to identify and halt new invasions. The Green Crab Control Committee recommends biweekly to monthly sampling of uninvaded water bodies to identify postlarval and young-of-year (YOY) crabs. Postlarval crabs are most likely to be found between April and June, while YOY sampling is most successful from August to September (Green Crab Control Committee, 2002).

In 1999, the Washington Department of Fish and Wildlife established a detective monitoring program for green crabs in Puget Sound, the Strait of Juan de Fuca, and the San Juan Islands. The department used baited crayfish traps, which were positioned at various locations in the regions and checked regularly by trained state officials or volunteers for the presence of green crabs (Holmes, 2001).²⁹

In addition to checking uninvaded areas to detect new introductions, the Control Committee recommends monitoring already invaded water bodies to forecast "outbreak" years, or years of high green crab recruitment.

7.3 Eradication, Control, and Mitigation

Once the green crab becomes established at a particular location, decision makers must choose whether to attempt to eradicate the population, control its size and further spread, or simply mitigate the impacts of the invasion. This decision depends largely on crab abundance, reproductive potential, and available control tools.

According to the Green Crab Control Committee, "eradication is most likely to be successful for small newly founded populations of green crab," preferably in isolated water bodies at the ends of

²⁸In 2002, the state of Oregon also established a Ballast Water Management Rule that requires ballast exchange for vessels engaged in Pacific nearshore voyages, (Or. Admin. R. 340-143-0010).

²⁹ This program is no longer active due to a lack of funding.

its range (Green Crab Control Committee, 2002). Continued monitoring of at-risk water bodies may result in early identification of new populations, when eradication is still feasible.³⁰ Once a crab population is established and begins to reproduce, complete eradication may be difficult, but population control may still help to minimize impacts and contain further spread. The strategies used to eradicate and control green crab populations are essentially similar, differing primarily in the goal and scale of the effort, and are described below. Note that though potential control strategies include chemical and biological control, as well as bounty system and fishery development, physical, selective trapping of green crabs remains the most viable and widely used eradication and control approach.

- **Green Crab Trapping/Capturing:** Modified crayfish and pit-fall traps have been used successfully to capture green crabs on the East Coast and in Washington State (Holmes, 2001). In Washington, a total of 1,100 crabs have been removed from Willapa Bay and Grays Harbor. The number of crabs caught per unit of effort declined from 1999 to 2001, before rising again in 2002 (WDFW, 2002; Holmes, 2001). It appears that the traps capture more male than female crabs, but this may be due to male territoriality or predation on the females (Dumbauld, as cited by Holmes, 2001). A green crab eradication program using these trapping methods is now underway in Bodega Harbor, California, with funding from NOAA.

According to David Grunden, the Oak Bluffs Shellfish Constable, trapping is also actively used in the town of Oak Bluffs, Martha's Vineyard, where about 70 traps are placed each year, particularly in areas where young shellfish reside. Research conducted by William Walton of the Barnstable County's Cape Cod Cooperative Extension & Woods Hole Oceanographic Institution Sea Grant suggests that this program should increase shellfish survival rates by 10 percent (Walton and Ruiz, 2004; Grunden, 2006). The program was privatized in 2003, and the town now provides the traps to a local fisherman who is trying to set up a bait fishery for the crabs. In 2002, when town personnel last tended the traps, a total of about 171,500 crabs were captured during the 26-week trapping period (Grunden, 2006).

After 20 years of trapping, the success of the program in controlling green crab populations in Oak Bluffs is unclear. On one hand, Walton's research indicates that the crabs found in ponds that had traps were generally smaller than in other ponds. At the same time, however, based on the estimated size of the crab population in the trapped ponds, the trapping program only "[scratches] the surface and [does not put] any real dent toward reducing their numbers" (Grunden, 2006).

- **Development of Bounty/Bait Market:** Another approach to controlling green crab populations is to develop financial incentives, in the form of a bounty program or bait fishery, to encourage the public to harvest the crabs. According to Bill Walton, a marine biologist who explored the feasibility of establishing a commercial green crab fishery on the East Coast, both of these incentive-based approaches have "proved largely ineffective" (Walton, as cited by Holmes, 2001). According to Holmes (2001), "setting a bounty is difficult because the monetary value must be just enough to create an incentive to fish." At the same time, setting the bounty too high may encourage purposeful introduction of green crabs to new locations (Holmes, 2001).

³⁰ Successful eradication of larger invasive species populations (albeit not green crab) has also been reported (Culver and Kuris, 2000).

- **Development of Non-Commercial Fishery:** Despite their small size, green crabs reportedly taste pleasant and have been used as food by some ethnic groups. Education programs that encourage recreational fishing for green crabs may help to control population size. Similar to bounty programs, however, this approach may inadvertently encourage further introductions (Holmes, 2001).
- **Chemical Control:** Although “both aerial pesticide application and the use of poison baits have been suggested as means of using chemicals to control green crab,” further research is necessary to identify effective pesticides that will not harm non-target species (Green Crab Control Committee, 2002). The pesticide carbaryl, which is currently being used to control burrowing shrimp in Washington, may be effective in controlling or eradicating green crab populations. The pesticide, however, is toxic to numerous other organisms, including fish, other aquatic invertebrates, bees, and humans (Holmes, 2001). Further study of the impacts on non-target species is required to ensure that the pesticide will not cause more harm than good.
- **Biological Control:** Biological control, or the use of natural predators or parasites to reduce invasive populations, has been suggested as a strategy for green crab control/eradication by several authors, including Lafferty and Kuris (1996); Yamada (as cited by Holmes, 2001); and Hoeg, Glenner, and Werner (1997, as cited by Holmes, 2001). Lafferty and Kuris recently studied the possibility of using the parasite *Sacculini carcini* to control green crab populations. They found that the parasite, which attacks and castrates green crabs in their native range, also infects non-target, native species (Green Crab Control Committee, 2002). Other parasites that have been suggested include *Carcinonemertes epialti* (an egg predator) and *Portunion maenadis*, which also castrates the crab (Lafferty and Kuris, 1996; Holmes, 2001). Lafferty and Kuris’s recent findings, however, highlight the need for further research into the risks associated with introducing a non-native parasite into a new environment. On both the East and West Coasts it may also be possible to increase the abundance of native crabs in order to increase competition and control green crab populations (Yamada as cited in Holmes, 2001; Hunt and Yamada, 2003; deRivera et al., 2005). Finally, Yamada (2001) studied the use of sex pheromones in monitoring and controlling the green crab.
- **Genetic/Molecular Control:** Genetic modifications, including the creation and introduction of an “inducible fatality” gene are currently being explored, but are only in the early stages of development (Green Crab Control Committee, 2002). Also known as “conditional fatality,” the inducible fatality gene causes its carrier to die when exposed to particular environmental conditions (Mississippi Interstate Cooperative Resource Association, 2006).
- **Mitigation:** Mitigation measures should be put in place when the green crab invasion has spread beyond the point where population size can be controlled. Mitigation strategies focus on protecting native resources rather than attacking the invader. Various protective measures, including fencing and bagging of seeds, have been used to protect soft-shell clams and other shellfish preyed upon by the green crab.

7.4 Public Expenditures on Green Crab Control Programs

In its *Management Plan for the European Green Crab*, the Green Crab Control Committee estimated the funds necessary to implement each aspect of its recommended management

program. Table 7-1 presents these estimates. It is important to note that these estimates may under-represent the total expenditures on the green crab control program. For example, according to the Green Crab Control Committee, an estimate of \$75,000 per year for field-based activities is only possible “with a considerable amount of ‘in-kind’ support resulting from contributed effort by research organizations, management agencies, and volunteer groups” (Green Crab Control Committee, 2002). Furthermore, expenditures are not included for tasks that were already underway at the time when the management plan was being developed. Nonetheless, these estimates provide a preliminary idea of the likely expenditures of implementing a green crab monitoring and control program while also summarizing the detailed measures involved in the prevention/containment; detection/forecasting; and eradication, control, and mitigation of green crab invasions in the United States.

Task	FY02	FY03	FY04	FY05	FY06	FY07- FY10
A. Prevention and Containment						
Pathway Analysis	\$15					
Contact Network						
Develop management strategy		\$15				
Implement Management Strategy						
Pathway Disruption			\$100	\$20		
Education and Outreach			\$50	\$25		
<i>Prevention and Containment Total</i>	\$15	\$15	\$150	\$45		
B. Detection and Forecasting						
Establish Network						
Pacific Coast						
Atlantic Coast						
Standardized Field Measures						
Pacific Coast		\$75	\$75	\$75	\$75	\$50
Atlantic Coast		\$50	\$50	\$50	\$50	\$50
Develop/implement environmental & forecasting methods		\$50	\$200	\$75	\$75	\$75
Contribute to implementation of early warning system						
<i>Detection and Forecasting Total</i>		\$175	\$325	\$200	\$200	\$175
C. Eradication, Control & Mitigation						
Develop decision tree for rapid response		\$50				
Demonstration Project(s)				\$100		
Implement rapid response and control program					\$100	\$100
<i>Eradication/Control/Mitigation Total</i>		\$50		\$100	\$100	\$100
D. Information & Data Management						
Establish information clearinghouse & website	\$30					
Maintain current information on workgroup activities, results, protocols, and links		\$5	\$5	\$5	\$5	\$5
Develop/Implement/Sustain Database		\$5	\$5	\$5	\$5	\$5

Table 7-1: Expenditures Associated with Implementing the Management Plan for the European Green Crab in the United States (\$000)						
Task	FY02	FY03	FY04	FY05	FY06	FY07- FY10
Archives, Images, Maps,& Data Graphics on Websites						
<i>Information/Data Management Total</i>	\$30	\$10	\$10	\$10	\$10	\$10
<i>Total, Management Plan Implementation</i>	\$45	\$250	\$485	\$355	\$310	\$285

Based on the cost estimates and implementation schedule presented in the management plan, green crab management/control expenditures will amount to roughly \$285,000 per year during 2007 to 2010. We will need to contact the agencies expected to implement the management plan, however, in order to learn which of the steps listed in Table 7-1 have already been completed.

8. Conclusions

The study revealed significant data limitations that rendered benefit cost analysis of green crab control programs not feasible. Specifically, there is no information on green crab population changes due to various management and control strategies. Nevertheless, the comparison of the estimated damages from green crab predation and the expenditures on green crab control suggests that development and implementation of such programs may benefit local economies (assuming that these programs are effective).

The estimated total losses from green crab predation to commercial and recreational shellfisheries and eelgrass restoration efforts range from \$18.6 to \$22.6 million per year (see Table 8-1). We note that these estimates do not account for damages caused by the green crab to a number of species such as oysters, winter flounder, and non-shellfish benthic populations as well as non-use values of the species included in the analysis.³¹ In addition, these estimates do not account for changes in the overall health of ecosystems invaded by green crabs and the associated change in the value of these ecosystems. In comparison, the estimated public expenditures for green crab management are only \$315,000 for years 2007–2010.³²

This comparison raises the question whether the current expenditures on green crab management and control programs are enough. Unfortunately, it is impossible to answer this question without better understanding of the effectiveness of the control programs, the ecological effects of green crab invasion, and the value of the resources affected by green crabs.

³¹ This analysis could be potentially expanded to include winter flounder and benthic populations.

³² As noted in Section 7-4, this estimate may significantly under-represent the total expenditures on green crab control programs.

Table 8-1: Total Estimated Damages from Green Crab Predation (Millions, 2006\$)				
Damage Category	Scenario 1^a		Scenario 2^b	
	Low	High	Low	High
Commercial Shellfishing - East Coast	\$14.70	\$18.70	\$14.70	\$18.70
Commercial Shellfishing - West Coast	\$0.00	\$0.00	\$0.58	\$1.14
Recreational Shellfishing - East Coast	\$3.84	\$3.84	\$3.84	\$3.84
Eelgrass Restoration - East Coast	\$0.06	\$0.08	\$0.06	\$0.08
Eelgrass Restoration - West Coast	\$0.00	\$0.02	\$0.00	\$0.02
Total	\$18.61	\$22.64	\$19.19	\$23.78
a. Scenario 1 assumes a low probability of invasion of northern Washington and Alaska.				
b. Scenario 2 (worst case) assumes a 100 percent probability of invasion of northern Washington and Alaska.				

This study is the first attempt at developing an integrated modeling framework for estimating economic impacts from green crab invasion. It revealed significant data gaps and highlighted the need for additional research, including:

- developing a more comprehensive green crab spread model that would include temporal factors, El Niño events and other ocean currents;
- collecting more empirical data on population effects from green crab predation and developing ecological damage functions for the affected species;
- understanding green crab impacts on ecosystem functionality;
- conducting nonmarket valuation studies that would allow estimation of the values of the affected resources (e.g., recreational shellfishing and ecosystem health).

Appendix A: Green Crab Densities

A1. East Coast Green Crab Densities

Table A-2 presents the quartile green crab density values observed in data obtained from Welch (1973–1978; 1981–1982), Seabrook Station (1978–2004), and the status of green crabs at eight Atlantic Coast sites (Virginia to Maine) report (C. deRivera, 2001–2002).

Table A-2: Quartiles, East Coast Green Crab Density Data	
Quartile	Density (CPUE)
Q1	27.40
Q2	76.20
Q3	133.15
Q4	410.00

To calculate annual historic and current losses on the East Coast, the random number generator function in Microsoft Excel was used to assign a density between the first and third quartile values in Table A-2 for each year in the time period considered. These densities are presented in Table A-3.

Table A-3: Assigned Densities	
Year	Randomly Assigned Density (CPUE)
1975	81
1976	45
1977	99
1978	61
1979	104
1980	45
1981	122
1982	110
1983	127
1984	39
1985	85
1986	117
1987	28
1988	46
1989	121
1990	47
1991	50
1992	50
1993	131
1994	106
1995	80
1996	58
1997	116
1998	120

Table A-3: Assigned Densities	
Year	Randomly Assigned Density (CPUE)
1999	94
2000	91
2001	94
2002	108
2003	30
2004	94
2005	91

A2. West Coast Green Crab Densities

Table A-4 presents the quartile green crab density values obtained by using averages over the entire time period, for which data were provided by T. Grosholz (2007). A minimum and maximum density is identified for each state, and a random density is generated for every year.

Table A-4: Quartiles, West Coast Green Crab Density Data	
Quartile	Density (CPUE)
Q1	0.9
Q2	3.3
Q3	8.4
Q4	31.5

To calculate future losses on the West Coast, the random number generator function in Microsoft Excel was used to assign a density between the first and third quartile values in Table A-4 for each year in the time period considered. These densities are presented in Table A-5.

Table A-5: Randomly Assigned Density (CPUE)	
Future Year	Randomly Assigned Density (CPUE)
0	10.52
1	28.94
2	22.07
3	30.43
4	21.82
5	29.24
6	3.19
7	20.13
8	28.03
9	0.71
10	24.76
11	31.23
12	17.28
13	10.34

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14	30.28
15	2.6
16	21.26
17	7.82
18	28.67
19	21.98
20	9.83
21	28.35
22	4.1
23	4.38
24	28.58
25	12.86

Appendix B: Recreational Shellfishing Supplemental Data

B1. Average Cost of Shellfishing Permits

The average cost of shellfishing permits by state is recorded in Table B-1.

Table B-1: Shellfishing Permit Fee by State				
State	Recreational Quahog Resident	Recreational Quahog Non-Resident	General Shellfishing Resident	General Shellfishing Non-Resident
Connecticut	-	-	\$15.14	\$34.92
Delaware	-	-	\$5.75	\$57.50
Massachusetts	-	-	\$15.67	\$58.33
Maine	-	-	\$18.83	\$35.92
Maryland	No license is required for recreational clamming, but there are restrictions on the daily take and the minimum size that can be kept.			
New Jersey	\$10.00	\$20.00	-	-
New York	-	-	\$10.00	-
Rhode Island	-	-	\$0	\$200.00
Virginia	-	-	\$12.50	\$12.50
<p><i>Note:</i> The permit fee for New Jersey is for quahog shellfishing only. All other fees are for a general shellfishing permit, which includes harvest of quahogs.</p> <p><i>Data Sources by State:</i> Connecticut: average of 14 towns from the following website: http://www.ct.gov/doag/lib/doag/pdf/recreational_shellfishing_statewide_updated_6_20_07.pdf; Delaware: http://delcode.delaware.gov/title7/c024/index.shtml; Maine: average of 12 towns for which information is listed at http://www.maine.gov; Massachusetts: from Damery and Allen, 2004; Maryland: http://www.dnr.state.md.us/fisheries/fishfacts/hard-shell_clam.asp; New Jersey: http://www.state.nj.us/dep/fgw/pdf/marine_clamlicapp.pdf; New York: http://www.dec.ny.gov/permits/33000.html; Rhode Island: http://www.dem.ri.gov/programs/bnatres/fishwild/mffees.htm.</p>				

B2. Median Household Income by State

The value of median household income by state for input to the benefit transfer function was determined by taking the average annual income by state from 2000 to 2004. The full set of data, from 1995 to 2004, is provided in Table B-2.

Table B-2: Median Household Income by State: 1995 to 2004 (2006\$)											
State	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Average Annual Income 2000 to 2004
Connecticut	\$52,842	\$53,859	\$55,070	\$57,420	\$61,177	\$58,709	\$60,729	\$59,822	\$60,212	\$58,780	\$59,650
Delaware	\$45,863	\$50,266	\$53,878	\$51,186	\$56,382	\$58,934	\$56,466	\$55,636	\$53,698	\$51,258	\$55,198
Maine	\$44,458	\$44,367	\$41,031	\$44,002	\$46,991	\$43,607	\$41,677	\$41,295	\$40,655	\$44,089	\$42,265
Massachusetts	\$50,651	\$50,502	\$52,613	\$52,281	\$53,211	\$54,708	\$59,483	\$55,865	\$55,818	\$55,493	\$56,273
New Jersey	\$57,675	\$60,699	\$60,123	\$61,516	\$60,138	\$58,981	\$58,935	\$61,146	\$59,330	\$58,967	\$59,472
New York	\$43,368	\$45,280	\$44,820	\$46,168	\$48,354	\$47,676	\$47,941	\$47,025	\$46,872	\$47,630	\$47,429
Rhode Island	\$46,429	\$47,296	\$43,566	\$50,232	\$51,655	\$49,376	\$52,050	\$47,530	\$48,979	\$51,136	\$49,814
<i>Sources:</i>											
Household Income: http://www.census.gov/hhes/www/income/histinc/h08.html											
Inflator: ftp://ftp.bls.gov/pub/special.requests/cpi/cpiiai.txt											

Appendix C: Predicted Probability of Invasion

Table C-1: Predicted Probability of Invasion							
4-Digit Major Watershed Code	Major Watershed Name	Watershed Name	Dummy =1 if Green Crab present	Estimated Probability	Assigned Probability	Confidence Interval _lower	Confidence Interval _Upper
Mid Atlantic Region							
M070x	Barnegat Bay	Barnegat Bay	0	0.214	0	0.029	0.715
M010x	Buzzards Bay	Buzzards Bay	1	1.000	1	0.482	1.000
M130e	Chesapeake Bay	James River	0	0.033	0	0.002	0.349
M130d	Chesapeake Bay	York River	0	0.010	0	0.000	0.401
M130g	Chesapeake Bay	Choptank River	0	0.048	0	0.003	0.506
M130a	Chesapeake Bay	Patuxent River	0	0.053	0	0.003	0.518
M130f	Chesapeake Bay	Chester River	0	0.050	0	0.002	0.619
M130c	Chesapeake Bay	Rappahannock River	0	0.059	0	0.002	0.652
M130b	Chesapeake Bay	Potomac River	0	0.417	0	0.045	0.916
M130h	Chesapeake Bay	Tangier/Pocomoke Sounds	1	0.143	0	0.006	0.833
M090x	Delaware Bay	Delaware Bay	1	1.000	1	0.005	1.000
M100x	Delaware Inland Bays	Delaware Inland Bays	1	0.765	1	0.086	0.991
M030x	Gardiners Bay	Gardiners Bay	1	0.999	1	0.349	1.000
M050x	Great South Bay	Great South Bay	1	0.731	1	0.094	0.986
M060x	Hudson River/Raritan Bay	Hudson River/Raritan Bay	1	0.977	1	0.031	1.000
M040w	Long Island Sound	Long Island Sound	1	1.000	1	0.000	1.000
M040a	Long Island Sound	Connecticut River	1	1.000	1	0.198	1.000
M020x	Narragansett Bay	Narragansett Bay	1	0.737	1	0.058	0.992
North Atlantic Region							
N040x	Blue Hill Bay	Blue Hill Bay	1	1.000	1	0.293	1.000
N100x	Casco Bay	Casco Bay	1	0.999	1	0.375	1.000
N020x	Englishman/Machias Bay	Englishman/Machias Bay	1	0.982	1	0.172	1.000
N130x	Great Bay	Great Bay	1	0.579	1	0.086	0.952

Table C-1: Predicted Probability of Invasion							
4-Digit Major Watershed Code	Major Watershed Name	Watershed Name	Dummy =1 if Green Crab present	Estimated Probability	Assigned Probability	Confidence Interval_lower	Confidence Interval_Upper
N090x	Kennebec/Androscoggin River	Kennebec/Androscoggin River	1	0.994	1	0.358	1.000
N170a	Massachusetts Bay	Boston Harbor	1	1.000	1	0.766	1.000
N150x	Merrimack River	Merrimack River	1	0.945	1	0.204	0.999
N060x	Muscongus Bay	Muscongus Bay	1	1.000	1	0.811	1.000
N030x	Narraguagus Bay	Narraguagus Bay	1	1.000	1	0.660	1.000
N050x	Penobscot Bay	Penobscot Bay	1	1.000	1	0.391	1.000
N110x	Saco Bay	Saco Bay	1	0.994	1	0.221	1.000
N080x	Sheepscot Bay	Sheepscot Bay	1	0.977	1	0.013	1.000
Pacific Region							
P200x	Alsea River	Alsea River	1	0.813	1	0.132	0.992
P260x	Columbia River	Columbia River	1	1.000	1	0.000	1.000
P170x	Coos Bay	Coos Bay	1	0.990	1	0.379	1.000
P120x	Eel River	Eel River	1	1.000	1	0.942	1.000
P280x	Grays Harbor	Grays Harbor	1	1.000	1	0.412	1.000
P140x	Klamath River	Klamath River	1	0.196	0	0.011	0.838
P070x	Morro Bay	Morro Bay	1	0.999	1	0.026	1.000
P250x	Nehalem River	Nehalem River	1	0.999	1	0.842	1.000
P290w	Puget Sound	Puget Sound	0	0.002	0	0.000	1.000
P290a	Puget Sound	Hood Canal	0	0.024	0	0.000	1.000
P290b	Puget Sound	Skagit Bay/Whidbey Basin	0	0.001	0	0.000	1.000
P150x	Rogue River	Rogue River	0	0.153	0	0.004	0.880
P090a	San Francisco Bay	Central San Francisco/San Pablo/Suisun Bays	1	1.000	1	0.192	1.000
P090w	San Francisco Bay	San Francisco Bay	1	0.991	1	0.122	1.000
P220x	Siletz Bay	Siletz Bay	1	0.773	1	0.068	0.994
P190x	Siuslaw River	Siuslaw River	0	0.896	1	0.285	0.995

Table C-1: Predicted Probability of Invasion							
4-Digit Major Watershed Code	Major Watershed Name	Watershed Name	Dummy =1 if Green Crab present	Estimated Probability	Assigned Probability	Confidence Interval _lower	Confidence Interval _Upper
P240x	Tillamook Bay	Tillamook Bay	1	1.000	1	0.816	1.000
P110x	Tomales Bay	Tomales Bay	1	1.000	1	0.636	1.000
P180x	Umpqua River	Umpqua River	1	0.727	1	0.076	0.988
P270x	Willapa Bay	Willapa Bay	1	0.999	1	0.381	1.000
P210x	Yaquina Bay	Yaquina Bay	1	1.000	1	0.586	1.000
South Atlantic							
S010x	Albemarle Sound	Albemarle Sound	0	0.043	0	0.000	0.978
S110x	Broad River	Broad River	0	0.112	0	0.001	0.943
S070x	North/South Santee Rivers	North/South Santee Rivers	0	0.673	1	0.116	0.970
S020b	Pamlico Sound	Neuse River	0	0.248	0	0.009	0.926
S020w	Pamlico Sound	Pamlico Sound	0	0.016	0	0.000	0.999
S020a	Pamlico Sound	Pamlico/Pungo Rivers	0	0.395	0	0.049	0.893
S060x	Winyah Bay	Winyah Bay	0	0.244	0	0.009	0.916

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