Modeling Economic Impacts of the European Green Crab

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Abstract

The European green crab, *Carcinus maenas*, is one of the most widely distributed invasive species in coastal systems. This species has become established on five continents and has produced significant negative ecological and economic impacts in many areas. On the Atlantic coast of North America, green crabs have been established for at least 180 years. On the Pacific coast, green crabs became established in San Francisco Bay in the late 1980s and expanded their range rapidly during the 1990s. In response to the spread and impacts of green crabs in the U.S., *Carcinus maenas* was listed as an "aquatic nuisance species" by the federal Aquatic Nuisance Species Task Force (ANSTF). To date, there have been no formal review of the ecological impacts of green crabs and no formal attempts to quantify and understand their potential economic impacts. This paper presents a predictive framework for understanding the magnitude and extent of green crab impacts on the East and West Coasts of the U.S. The framework consists of several linked models. The ecological sub-models incorporate green crab dispersal and relationship between green crab abundance and the dynamics of prey populations. The economic analysis focuses on the green crab impacts on commercial shellfisheries and estuarine restoration efforts. The documented historical and present impacts of green crabs on the shellfishery include soft-shell clams, blue mussels, scallops, hard shell clam, and manila clams. The preliminary results of this analysis show that damages to commercial shellfishery from Green Crab predation are on average \$22.6 million per year on the East Coast of the United States. Although the current damages on the West Coast are negligible, the potential future damages are likely to increase to \$0.84 million per year, if Green Crab invades Puget Sound (WA) and Alaska.

Modeling Economic Impacts of the European Green Crab

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 (U.S.) 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 temporal and spatial scale of AIS impacts relative to other environmental concerns in the U.S. is needed to determine if intervention is required and if so, to help design and implement cost-effective management options. The National Atmospheric and Oceanographic Administration and the United States Fish and Wildlife Service jointly administer, with the participation of U.S. EPA and other agencies, the Federal Aquatic Invasive Species Control Program, established by the National Invasive Species Act, and in 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 at 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. The framework is applied to a case study of European green crab impacts.

The goals of the case study are to estimate the current and historical impacts of the European green crab on ecosystem services on the East Coast of the United States and to estimate the current and potential future impacts of the European green crab on ecosystem services on the West Coast of the United States under various invasion scenarios. The framework described in this paper links ecological models of green crab impacts on ecosystem services with economic models that value changes in those services. The ecological sub-models incorporate green crab dispersal and relationship between green crab abundance and the abundance of prey populations. The economic analysis estimates the economic consequences, primarily those on shellfishery harvests and estuary restoration efforts.

European Green Crab Invasion

The European green crab (C*arcinus maenas*) is native to Northern Europe, and has established populations in North America, South Africa, Japan, Argentina, and Australia. Green crabs are capable of surviving in water temperatures ranging from 0° 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° to 26° C and generally increases as salinity increases. 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. Assuming two reproductive events per annum, a single female may produce as many as 370,000 eggs per year. *C. maenas* are also tolerant of a variety of habitats, including unstructured sandy and muddy bottoms, saltmarshes and seagrass beds, and rocky substrate" (Green Crab Control Committee 2002). Although the crabs prefer sheltered estuarine waters, they can also survive in outer coastal environments up to 180 feet deep (Cohen 1997).

Despite their small size, 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. Studies reveal that *C. maenas* eats a variety of organisms including species from at least 104 families and 158 genera within 14 animal and five plant and protozoan phyla. An examination of the stomach contents of *C. maenas* reveals that their main prey include mussels, clams, worms, snails, seaweeds (algae), barnacles, isopods, and other crustaceans (Cohen 1997).

Invasion History

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, Carlton, and Fountain 1995). The green crab's current East Coast range extends from Maryland to Prince Edward Island, Nova Scotia (Audet et al. 2003). Since 1989, these crabs have greatly expanded their West Coast range and are now established in bays and estuaries stretching from Monterey Bay, CA to Brooks Peninsula, BC (Green Crab Control Committee 2002; Grosholz et al. 2000; Jamieson 2006). 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, settling on sand and mud, in shallow, protected waters instead (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.

The green crab's ability to adapt to a broad range of environments and its high reproductive rate make it likely that it will continue invading new areas on the West Coast. 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 is likely to have occurred via dispersal of planktonic larvae.

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 Geller 2001). As such, both introductions were most likely human-mediated. Following a detailed review of *C. maenas* literature, Carlton and Cohen (2003) conclude that natural methods of transport on ocean currents does not appear to be responsible for introduction into the U.S. Cohen, Carlton, and Fountain (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. Since wooden vessels are no longer used, ship fouling/boring is no longer a viable dispersal mechanism. Because *C. maenas* are able to survive for an extended period of time outside of water and without food, they could have survived a transoceanic journey among stones used as solid ballast (Carlton and Cohen 2003).

Incidental transport with commercial fishery products is the most likely vector for the initial *C. maenas* introduction to the West Coast, although other possible means include ballast water and bait shipments (Cohen 1997, Carlton and Cohen 2003). 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 ballast water (Carlton and Cohen 2003; Cohen, Carlton, and Fountain 1995). *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. The organisms may have been accidentally or intentionally released from educational or research institutions**.** The crabs may have been brought over to the West Coast and released on purpose, in order to establish a new crab fishery.

Unlike transoceanic green crab introductions, 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 man-made vectors. 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 (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.

Future Spread of Green Crab

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).

This study relies on empirical data to identify the current and historical habitat range of green crabs (DeRivera, Gillespie, Grosholz, Preissler, Ruiz, Schlosser, Yamada, Wasson, unpubl. data). To estimate the potential future impacts of the European green crab on commercial shellfisheries on the West Coast, we used the GARP (Genetic Algorithm for Rule-set Prediction) 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 (De Rivera et al. 2006). For the purpose of this study we assume that the current green crab densities will be observed within the entire future habitat range.

Ecological Impacts

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, once introduced, their populations can grow rapidly 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. Since their initial introduction and establishment in North America, the European green crab has been associated with the decline of a number of native aquatic species including clams and shore crabs due to predation or competition, or indirect effects on habitat (Grosholz and Ruiz 1995, 1996; Cohen 1997; Grosholz et al. 2000; Grosholz 2005).

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 the potential to affect a number of ecosystem goods and services, including commercial and recreational shellfish harvests, habitat suitability, nutrient processing, ecosystem regulatory functions, and recreation such as wildlife viewing.

Two of *C. maenas*' preferred food sources include the soft-shell clam (*Mya* spp.), which supplies one of the most important commercial clam fisheries in the U.S., and the blue mussel (*Mytilus* spp.). The green crab is 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 central California, green crabs had significant impacts on Manila clam fisheries during their first few years of introduction to this region. In Tomales Bay, green crab predation resulted in losses of nearly 40% of the annual production of 5,500 kg of Manila clams for one producer in 1996 (Grosholz et al. 2001).

The green crab can also affect the habitat suitability of areas where it is found and therefore, affect biodiversity and ecosystem functioning. 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). While foraging, *C. maenas* reworks the uppermost portion of sediments in the intertidal mud flats. This can cause considerable damage to the estuarine and coastal ecosystems because it results in the cutting and tearing of eelgrass shoots' sheath bundles (Davis, Short, and Burdick 1998).

The green crab preys upon many aquatic species that also serve as a food source for migratory shorebirds (Grosholz and Ruiz 1995, 1996; Grosholz et al. 2000; Grosholz 2005). Thus recreational activities, other than recreational shellfishing, that could be affected include bird watching. For example, in Bodega Harbor, CA, 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).

This case study focuses on two types of green crab impacts: (1) impacts on commercial shellfish harvests and (2) eelgrass restoration efforts. The best understood and quantified are impacts on commercial and sport shellfisheries. Of these, the best known impacts have been the historical and present impacts on the fishery for soft-shell clams *Mya arenaria*. Green crabs have been blamed for the collapse of the soft-shell clam fishery in northern New England and maritime eastern Canada (Smith and Chin 1955; Glude 1955; MacPhail, Lord, and Dickie 1955) as well as continuing to be a significant predator to the present (Ropes 1968; Welch 1969; Beal and Kraus 2002; Beal 2006a,b). Commercial impacts have also been documented or alleged for other shellfisheries in eastern North America including blue mussels, manila clams, scallops, and hard shell clams (Barbeau et al. 1996; Walton 2001; Miron et al. 2005).

Green crabs may also affect the success of eelgrass restoration efforts. Mesocosm studies (Davis, Short, and Burdick 1998) have shown that the foraging activities of green crabs disturb newly planted eelgrass plants and may significantly affect the success of these plantings. The costs of restoring eelgrass habitats can be substantial and there is the potential for green crabs to significantly influence the success of this process.

Green Crab Impacts on Shellfisheries

As noted above, there are documented historical and present impacts of green crabs on the soft-shell clam, scallop, hard shell clam, blue mussel, and manila clam shellfisheries. There are also documented historical and present impacts of green crabs on the oyster shellfishery and the winter flounder fishery, though damage functions for these species are not currently available, and therefore their damages are not included in the estimated losses. 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.

Data

The data used in the analysis came from five species-specific studies on the effect of European green crab densities on shellfish losses. These studies include an examination of the losses of (1) soft-shell seed clams (*Mya arenaria*) in Rowley River, MA, in 2001 (Massachusetts Department of Fish and Game, unpubl. data.); (2) Manila clams (*Venerupis philipinarum*) in Tomales Bay, CA, from 1996 to 1999 (Grosholz et al. 2001); (3) mussels (*Mytilus edulis*) in Menai Straits, North Wales, from 1972 to 1973 (Dare and Edwards 1976); (4) northern bay scallops (*Argopectin irradians irradians*) in Poquonock River, CT, from 1983 to 1984 (Tettelbach 1986); and (5) hard-shell clams or quahogs (*Mercenaria mercenaria*) in Martha’s Vineyard, MA 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 there being no statistical difference in the predator-prey functional relationship between the two types of shellfish.

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):

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

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 represents the shellfish losses at which the crabs reach a saturation point and therefore the level at which the losses reaches asymptotically at high crab densities. The results shown in Table 1 below, suggest that the level at which the losses reach an asymptote is approximately 40 percent.

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. Further 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” (henceforth CPUE), which represent relative densities based on generally standard trapping methods. To determine the cut-off point where the damage function shifts from linear to sigmoid, we estimated switching regressions with cut offs at 10, 20 and 30 crab CPUE. The model where the cut-off is 30 CPUE was found to fit the data best. Therefore, this study assumes that the predator-prey relationship is linear for CPUE less than 30 and that it follows Type II (i.e., sigmoid) functional relationship for CPUE above 30. Therefore, we estimated the following model:

$$\text{Shellfish Losses}_i = \begin{cases} b_0 * \text{Crab Density}_i + e_i & \text{if Crab Density} < 30 \\ \dfrac{b_1}{(1 + \exp(-b_2 * \text{CrabDensity}_i))} + u_i & \text{if Crab Density} > 30 \end{cases} \tag{2}$$

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. 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 3.

Economic Impacts on Shellfisheries

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. Producer surplus provides an estimate of the economic damages to commercial fishers, 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 an input the expected change in harvest and baseline gross revenues, and provides as outputs the expected change in producer and consumer surplus.

Because most shellfisheries are regulated with quotas or restrictive permits, there will be lasting economic damages to commercial fishers. 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 theory, producer surplus (net benefit) is equal to normal profits (total revenue minus fixed and variable costs), minus opportunity cost of capital. The fixed costs and inputs are incurred independent of the expected marginal changes in the level of shellfish landings. Variable costs such as ice and other supplies, however, directly vary with the level of landings. Furthermore, since opportunity cost of capital is estimated only to be about 0.4 to 2.6% 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 surplus is calculated as a species- and region-specific percentage (also called "net benefit ratio") of the change in gross revenue due to increased landings. If changes in landings are such that a price change is anticipated, the change in revenues may be either positive or negative, depending on the relative elasticity of demand.

In general, the analysis of market impacts involves the following steps (Bishop and Holt 2003):

- Assessing the net welfare changes for shellfish consumers due to changes in shellfish harvest and the corresponding change in shellfish price;
- Assessing net welfare changes for shellfish harvesters due to the change in total revenue, which could be positive or negative.

- Calculating the increase in net social benefits when the shellfish harvest quota changes.

Data

To estimate damages to commercial fisheries from European green crab predation, we first collected data on historic and current landings for affected species, including manila clams (West Coast only), soft-shell clams, hard-shell clams, and blue mussels, and bay scallops (East Coast only). The National Oceanic and Atmospheric Administration's (NOAA's) National Marine Fisheries Service (NMFS) provided information on the quantity and ex-vessel value of commercial fishery landings for years 1975 to 2005 by state, species and state (NOAA 2007).

For the West Coast analysis, we contacted the states of California, Oregon, Washington and Alaska to obtain shellfish landings data by state, species, and waterbody. Waterbody-specific data were needed because the European green crab has not yet spread to all waterbodies on the West coast. Thus, using statewide landings data could overestimate current shellfishery losses.

Clam and mussel landings data from NMFS and state agencies includes both wild harvest and harvest from aquaculture. Because aquaculture often includes measures to minimize predation on their stocks, the impact of European green crabs on these species is partially mitigated. Additionally, the costs associated with raising shellfish are different from costs associated with harvesting wild shellfish. To supplement the shellfish landings data, data on state and/or regional aquaculture production were obtained from a variety of sources and the appropriate adjustments were made to the analysis. Data on the percent of shellfish harvest derived from aquaculture on the West Coast were obtained directly from the state agencies. Data on the aquaculture value of East Coast clam and mussel production were obtained from R. Langan (unpubl. data).

Information on the variable costs incurred by the shellfish industry as a proportion of their revenues was obtained 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. Finally, this analysis relies on Cheng and Capps' (1988) estimate of the elasticity of demand for all shellfish in calculating the shift in the price of shellfish due to a change in shellfish supply. Cheng and Capps estimated that the demand for shellfish is slightly inelastic, with an own-price elasticity of –0.885.

Results

As shown in Table 3, the estimated average annual losses to shellfisheries on the East Coast due to green crab predation are $22.6 million. The estimated total historic losses on the East Coast during 1975 – 2005 are $699.1 million.

Tables 4 and 5 present 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 $0.84 million per year. As shown in Table 6, the total present value of potential commercial harvest losses due to green crab predation over 25 years is $21.7million.

All monetary values are in 2006 dollars; the annualized and present values were estimated using a 3 percent discount rate. All calculations assume that predator netting used in aquaculture on average prevents 34 percent of aquaculture losses (Beal and Kraus 2002).

Green Crab Effects on Eelgrass Restoration

As noted above, green crabs may also affect the success of eelgrass restoration efforts. For example, during eelgrass restoration efforts in 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 one month (F. Short, Univ. of New Hampshire, pers. comm. A laboratory study was undertaken to further investigate this relationship. Using varying green crab densities, the study indicated that as much as 39% of the transplanted eelgrass was lost within one week of green crab exposure (Davis, Short, and Burdick 1998). Another study showed that green crab disturbance resulted in the total loss of acre-size plots in a matter of weeks (F. Short, pers. comm.). The costs of restoring eelgrass habitats can be substantial and there is the potential for green crabs to significantly influence the success of this process.

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 to estimate the monetary value of damages to eel grass 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.

Green Crab Bioturbation

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

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

$$\text{Eelgrass Losses} = \frac{b_0 * \text{Crab Density}^{b_2}}{b_1^{b_2} + \text{Crab Density}^{b_2}} \qquad (3)$$

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 7. This function reflects the asymptotic relationship between green crab density and eelgrass losses seen in Davis, Short, and Burdick (1998), likely due to interference interactions among green crabs at the highest densities.

Estimating Economic Damage

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 projects that occurred between 1995 and 1999, an average of 7.41 acres of eelgrass was restored in California per year. The annual average number of restored eelgrass acres was used in conjunction with a range of green crab densities (0.01 CPUE, 15.755 CPUE, and 31.5 CPUE) and the estimated damage function to determine what percent of Californian eelgrass restoration projects was potentially lost due to European green crab bioturbation.

The cost of restoring an acre of California eelgrass is approximately $35,417 (Boyer 2007). This cost per acre was applied to the estimated acres lost due to the European green crab to estimate a monetary value of eelgrass restoration effort losses. Table 7 summarizes results of this analysis. The estimated losses to eelgrass restoration projects range from 2.3% to 18% of the total acres restored. The estimated annual value of damages to the eelgrass restoration projects for the state of California ranges from $6,152 to $47,018 (2006$).

For the East Coast analysis, we obtained the relevant data thorough queries of federal and state databases (EPA’s Restoration Project Directory, Coastal America.com’s Regional Conservation Projects, etc.). These queries produced 11 eelgrass restoration projects undertaken since 2001 in the East Coast states invaded by European green crab. Based on these data, 6.97 acres of eelgrass are restored per year in the affected states. The cost of restoring an acre of eelgrass on the East Coast is $49,382 (Leschen 2007).

To estimate the percentage of eelgrass acres lost due to green crab bioturbation, we combined data on green crab densities for the East Coast with the estimated eelgrass damage function. We then applied the cost of restoring an acre of eelgrass to the estimated number of acres lost due to green crab bioturbation. Results of this analysis are shown in Table 8. The estimated loss of eelgrass acres due to green crab bioturbation ranges from 17.5% to 22.5% depending on the green crab densities. The annual value of damages to eelgrass restoration projects ranges from $60,150 to $77,433 (2006$). We note that the value of damages to eelgrass restoration projects may be underestimated because comprehensive information on eelgrass restoration projects is not available.

Other Costs

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. It is important to note that these estimates may under-represent the total cost of a 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, costs are not estimated for tasks that were already underway at the time when the management plan was being developed. None-the-less, these estimates provide a preliminary idea of the likely costs 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 U.S.

Based on the cost estimates and implementation schedule presented in the management plan, green crab management/control costs will amount to roughly $285 thousand per year during 2007 to 2010.

Conclusions

This paper reports preliminary experience with the application of an integrated framework to examining the ecological and economic effects of green crab invasions on the East and West Coasts of the U.S. To our knowledge, it is the first formal attempt to understand and quantify a broad range of ecological and economic impacts of green crab invasions. The paper presents the results from the case studies of green crab impacts on shellfish, including soft-shell clams, hard clams, Manilla clams, and mussels. In addition, the paper discusses impacts of green crab foraging activities on eelgrass restoration efforts. The estimated impacts are $22.6 million per year on the East Coast. The estimated economic impacts are negligible for the West Coast under current conditions; The West Coast impacts could increase to $0.84 million per year if the green crab were to spread up to Alaska. In addition, the estimated annual value of damages to eelgrass restoration projects ranges from $60 to $77 thousand and from $6 to $47 thousand on the East and West Coasts, respectively.

In future work on this framework, the ecological model could be improved to combine a description of both spatial location of uninvaded sites and potential sources as well as a description of local features that may influence the susceptibility of the site to be invaded (e.g., salinity, temperature range, and substrate type). The regression model would then allow us make predictions about the likelihood that particular bays and estuaries will be invaded given a suite of site characteristics and distance from sources of invasion.

In addition to the impacts estimated in this paper, we considered including broader ecological impact endpoints within the ecological submodels, but linking these endpoints to economic data is beyond the scope of this study due to the lack of quantifiable correspondence between the relevant ecological endpoints (e.g., Estuarine Biotic Integrity Index, effects on recreational shellfishing, fishing, shorebirds and recreational birding) and existing ecological data or resource valuation data. Future work in estimating the economic impacts of AIS should include quantifying and valuing a more extensive range of impacts on ecosystem services.

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Table 1. 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	0.39	0.22	1.84
b_1	0.07	0.17	0.39

Number of Observations: 21

R-Square: 0.65

Adjusted R-Square 0.61

F(2, 19) = 17.44, Prob >f = 0.0001

Non-linear estimation. Standard errors are asymptotic approximations.

Table 2. Green Crab Damages to Shellfisheries– West Coast

Dependent Variable: Percentage loss of shellfish.

Independent Variable: Crab Densities

Parameter	Parameter Estimate	Standard Error	t-statistic
Linear Segment < 30 Crab CPUE			
b_0	0.01	0.002 (robust)	5.73 (robust)

Number of Observations: 15

R-Square: 0.80

F(1, 14) = 32.79, Prob >f = 0.0001

Parameter	Parameter Estimate	Standard Error	t-statistic
Sigmoid Segment > 30 Crab CPUE			
b_1	0.68	0.959	0.05
b_2	0.03	0.989	0.01

Number of Observations: 8

R-Square: 0.81

Adjusted R-Square 0.751

F(2, 6) = 13.14, Prob >f = 0.0064

Non-linear estimation. Standard errors are asymptotic approximations.

Table 3. Estimated Total and Annual Losses from Green Crab Predation on the East Coast (millions, 2006$)

	Total Losses (1975-2005)		Average Annual Losses	
Species	Pounds	2006$[a]	Pounds	2006$[a]
Hardshell Clam (Quahog)	141.3	$422.0	4.6	$13.6
Softshell Clam	82.3	$198.7	2.7	$6.4
Blue Mussel	82.8	$25.9	2.7	$0.8
Bay Scallop	12.8	$52.5	0.4	$1.7
Total, All Species	306.4	$699.1	9.9	$22.6

[a] Measured as the total value of consumer and producer surplus lost.

Table 4. Estimated Current Annual Losses due to Green Crab Predation on the West Coast (thousands)

	California		Oregon		Washington		Alaska		Total	
Species	lbs	2006$[a]	lbs	2006$[a]	lbs	2006$[a]	lbs	2006$[a]	lbs	2006$[a]
Pacific Littleneck Clam	-	$0.0[b]	0.003	$0.002	-	$0.0[b]	-	$0.0[b]	0.003	$0.002
Softshell Clam	-	$0.0[b]	0.0[b]	$0.0[b]	-	$0.0[b]	-	$0.0[b]	0.0[b]	$0.0[b]
Manila Clam	1.1	$0.6	-	$0.0[b]	0.4	$0.2	-	$0.0[b]	1.5	$0.8
Blue Mussel	0.3	$0.2	-	$0.0[b]	-	$0.0[b]	-	$0.0[b]	0.3	$0.2
Total, All Species	1.4	$0.8	0.003	$0.002	0.4	$0.2	-	$0.0[b]	1.8	$1.0

[a] Measured as the total value of consumer and producer surplus lost.

[b] Positive value greater than zero.

Table 5. Estimated Future Annual Losses due to Green Crab Predation on the West Coast (thousands)[a]

	California		Oregon		Washington		Alaska		Total	
Species	lbs	2006$[b]	lbs	2006$[b]	lbs	2006$[b]	lbs	2006$[b]	lbs	2006$[b]
Pacific Littleneck Clam	-	$4.0	0.1	$0.5	21.5	$13.1	12.6	$7.5	34.3	$25.1
Softshell Clam	-	$3.2	0.01	$0.3	112.0	$17.7	-	$0.06	112.0	$21.3
Manila Clam	3.3	$102.8	-	$10.3	1,259.5	$541.6	-	$1.9	1,262.8	$656.6
Blue Mussel	64.3	$42.5	-	$2.2	281.1	$96.0	0.3	$0.5	345.8	$141.1
Total, All Species	67.7	$152.6	0.2	$13.3	1,674.2	$668.4	12.9	$9.9	1,755.0	$844.1

[a] Annualized over 25 years at a 3% discount rate.

[b] Measured as the total value of consumer and producer surplus lost.

Table 6. Total Present Value of Potential Consumer and Producer Surplus Losses Over 25 Years on the West Coast (million 2006$)[a]

	California	Oregon	Washington	Alaska	Total
Pacific Littleneck Clam	$0.1	$0.01	$0.3	$0.2	$0.6
Softshell Clam	$0.1	$0.01	$0.5	$0.002	$0.5
Manila Clam	$2.6	$0.3	$13.9	$0.05	$16.9
Blue Mussel	$1.1	$0.06	$2.5	$0.01	$3.6
Total, All Species	$3.9	$0.3	$17.2	$0.3	$21.7

[a] Present value of losses calculated at a 3% discount rate.

Table 7. 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.

Table 8: 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)	7.41	2.3%	0.17	$35,417	$6,152
Midpoint (15.755)	7.41	15.8%	1.17	$35,417	$41,367
High (31.5)	7.41	17.9%	1.33	$35,417	$47,018
East Coast [b]					
Low (27.40)	6.97	17.5%	1.22	$49,382	$60,150
Mean (76.20)	6.97	20.7%	1.44	$49,382	$71,341
High (133.15)	6.97	22.5%	1.57	$49,382	$77,433

[a] *California Sources: Davis, Short, and Burdick 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.*