Management Plan for the European Green Crab

Submitted to the Aquatic Nuisance Species Task Force

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Green Crab Control Committee
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Executive Summary

The European Green Crab *Carcinus maenas* is one of the most successful invasive predators in coastal marine systems having established populations on five continents. The ecological and economic damage caused by the green crab has been well documented for several global regions, including both coasts of North America. On the Atlantic coast of North America, the green crab has been an established invader for at least 180 years, although its geographic range expanded episodically during this period and is presently expanding on the northern end of its range. The species is a recent invader along Pacific shores, arriving in the late 1980s, and is in a much earlier stage of range expansion and population growth.

Recognizing the ecological and economic impacts of green crabs, as well as the extensive and expanding geographic range of the crabs in North America, Carcinus maenas was the first marine organism to be designated as an aquatic nuisance species by the Aquatic Nuisance Species Task Force (ANSTF). Following designation in November 1998, the ANSTF called for development of a Management Plan. In 2000, the Green Crab Committee was appointed by the to develop the Management Plan. The European Green Crab Management Plan is the result of several years of planning and research that culminated in two meetings of the Control Committee, in December 2000 in Gladstone, Oregon and in February 2001 in Davis, California.

In this plan, we evaluate the feasibility of management options for each prevention, eradication, and control of *Carcinus maenas* in the United States. We also outline plans for coordinating the activities of agencies scientists, and other concerns as well as developing a plan for information and data management. The plan is structured as a phased implementation plan that includes approximate timetables and costs of priority tasks as well as the entities responsible or most likely to complete those tasks. The management strategies available to limit the impact of the European green crab, as well as other invaders, include a combination of prevention, eradication, and control measures. Prior to colonization, prevention measures can be used to reduce the probability of transfer from any one of multiple transport vectors. Once a site is colonized, eradication efforts can be used to eliminate the population. If eradication is unsuccessful or not considered feasible, control measures may able to reduce the invading population and its undesirable impacts. Education and outreach as well as coordination of activities and information management are a foundation for all of these activities and are explicitly developed as well.

We present an implementation plan that is developed in phases over an 8-10 year period. This plan includes specific action items or tasks, suggested or actual funding sources for the tasks, entities responsible for implementing those tasks and a timetable for execution and completion of those tasks. As a result of completing the tasks listed in the phased implementation of this plan, a number of deliverables will result, many of which will have benefits far beyond the Green Crab invasion. These include:

1) A model detection—rapid response network that will facilitate a rapid response in reaction to any newly identified invasion or range expansion.
2) An expanding predictive capability regarding when and where new invasions are most likely to occur.
3) A process for vector management that will be applicable to a wide range of current and potential invaders
4) A system for information access and public outreach that will coordinate efforts and organize and standardize available information
5) Examples of demonstration projects for eradication and control that can be use in future green crab range expansions or with other invasions.

I. Introduction

The European green crab *Carcinus maenas* is now one of the most ecologically potent and economically damaging predators in nearshore coastal communities of both eastern and western North America. Green crabs have also been a notorious and successful aquatic invader worldwide with established populations South Africa, Japan, and Australia (Gardner et al. 1994, Thresher 1997, Geller et al. 1997). Native to northern Europe, green crabs colonized eastern North America in the early 19th century and now occur abundantly from Nova Scotia to Maryland (Williams 1984). In contrast, green crabs are a recent arrival to western North America, where they successfully colonized San Francisco Bay, California, in 1989-90. Their impacts on both natural ecosystems and commercial fisheries are well established (Ruiz et al. 1997, Grosholz 2002, Grosholz et al. 2002) as is their ability to rapid expand their range (Grosholz 1996).

Based upon panel review of a proposal to the Aquatic Nuisance Species Task Force in 1998 (Appendix 1), the green crab was formally recognized as an Aquatic Nuisance Species. As the result of this formal recognition, we have developed this management plan in response to the need to manage the expanding invasion of the European green crab at the national level. The overall goal of this document is to develop a management plan for the European green crab in the United States. We begin by presenting a summary of our current understanding of the distribution and ecology of *Carcinus maenas* as well as the known ecological and economic impacts associated with its invasion. We then develop the details of the management plan in the following sections: Section 2 -- Prevention and Containment, Section 3 -- Early Detection and Forecasting, Section 4 -- Eradication, Control, and Mitigation, Section 5 --Information Access and Data Management. In the final Section 6, we develop the overall structure for the management plan including a matrix of tasks, with estimated costs, and entities responsible for each task. Finally, we also provide additional details regarding the spread, distribution, ecology, and impacts of green crabs in an appendix (Appendix I) and a comprehensive list of references.

Summary of Spread and Distribution

The western North America invasion has undergone a rapid range expansion with green crabs expanding their range over 750 km in less than ten years since their initial invasion. Green crabs are now firmly established in every significant bay and estuary from Monterey Bay, CA (36^{o} N) to Gray's Harbor, WA (46^{o} N) (Cohen et al. 1995, Grosholz et al. 2000, Yamada 2001) and have the potential to become established from the Gulf of Alaska to Baja California (Cohen et al. 1995). The uniformity of the green crab distribution strongly suggests that this rapid range expansion has been largely, if not entirely, the result of planktonic dispersal of larval stages of the crab, and not the result of movement with shellfish products or other human activities, although these vectors may have accelerated the spread to some areas. In eastern North America, where green crabs have been established since the last century, green crabs have also recently (in 2000) continued to expand their northern range in eastern North America having invaded the Gulf of St. Lawrence at Prince Edward Island, Canada (47^{o} N) (G. Jamieson, Fisheries and Oceans, Canada, pers. comm.).

The evidence from North America as well as other invasions (South Africa, Australia) strongly support the idea that green crabs can rapidly expand their range quickly once becoming established (Grosholz 1996). Our most current evidence indicates that the green crab distribution in not static in either eastern or western North America. Particularly in western North America, the green crab distribution is likely to continue to expand (Cohen et al. 1995) with its impacts growing as it does so (Grosholz et al. 2000).

Summary of Biology and Ecology

Green crabs are both eurythermic and euryhaline and can survive a range of temperatures from freezing to 30^{o}C, and reproduction is reported from 3-26 ^{o}C. They are also reported to survive in a broad range of salinities, from 1.4 to 54 parts per thousand (ppt), although they are usually found in waters from 10-33 ppt. Larval stages are less tolerant to extremes in temperature and salinity than postlarval crabs, and successful development generally increases with increasing salinity (Williams 1984, Dawirs 1985).

Green crabs are able to utilize a broad range of habitat types. Postlarval crabs occur abundantly in the intertidal and subtidal zone, occurring as deep as 55 m. They occur in unstructured sandy and muddy bottoms, are commonly found in saltmarshes and seagrass beds, and also utilize woody debris and rocky substrate. These habitats span a wide range of exposure gradients, from protected embayments to exposed outer coasts. Despite the wide range of habitats reported for *Carcinus maenas* in Europe and eastern North America, the utilization of rocky habitats appears to be relatively limited in western North America (Grosholz & Ruiz 1996, unpubl. data). For example, green crabs are very common and ecologically important in rocky intertidal communities of eastern North America (Menge 1983, 1995), the use of sheltered rocky habitat appears to be uncommon in western North America. Although, it is evident that larval and postlarval green crabs have a variety of predators, from fish and birds to mammals and invertebrates, their effect on crab distribution abundance is uncertain. Within its present ranges, *Carcinus maenas* is often the most abundant crab species is soft-sediment bay and estuaries of Europe, Australia (Tasmania), and both coasts of North America (Tettlebach 1986, W. Walton unpubl. data, Grosholz et al. 1998, Ruiz et al. 1998).

Along with their wide range of environmental and habitat tolerances, the green crabs exploit a wide range of prey types. Reported preys include molluscs (clams and snails), crustaceans, annelids, fish, and algae. Although there is considerable variation in diet among sites, molluscs and crustaceans are numerically often the most abundant prey consumed (Grosholz & Ruiz 1996). In New England during colder winter months, green crabs move out of intertidal areas and into deeper water, where it is presumed they experience a significant reduction in activity. However, in California, there does not seem to be a similar change in distribution and predation by green crabs remains largely unchanged throughout the year.

The growth, reproduction and length of time required for development for green crabs depends upon temperature and salinity conditions, as well as food availability. Although green crabs can reach sexual maturity within one year, this appears to vary among geographic regions. It typically takes 2 years to reach maturity in northern Europe, whereas crabs appear to mature earlier in North America and Australia (Grosholz & Ruiz 1995, unpubl. data). Furthermore, crabs also appear to grow more rapidly and reach a larger size along both coasts of North America and Australia when compared to crabs in the native range (Grosholz & Ruiz 1996, Ruiz et al. 1998, Kuris et al. unpubl. data). Females can mate multiple times within a single year, and females may produce more than one clutch per year (Yamada 2002). The number of eggs per reproductive event varies by female size, and a typical female will produce 185,000 or more eggs/event. Eggs are brooded externally by the female and hatch into plankton larvae after 17-80 days. It takes approximately 90 days for larvae to develop through 4 successive zoeal stages and then metamorphose into benthic-dwelling, postlarval crabs.

Summary of Ecological and Economic Impacts

It is now well documented that the green crab is strongly influencing marine and estuarine communities in western North America (Ruiz et al. 1997, Grosholz et al. 2000, Grosholz 2002). Several native species have declined by more than 90% as the direct result of green crab predation (Grosholz et al. 2000). Green crabs have also had substantial impacts (up to 40% of production in some years) on some commercially important clam species (Grosholz et al. 2002). The direct effects of green crab predation in invaded communities may also have indirect effects on feeding rates and foraging efficiency of shorebirds, which depend on the invertebrates depleted by green crabs (R. Estelle, unpubl. Data).

Recent studies also suggest that there is a high potential for losses to commercial fisheries as the result of green crab predation. Lafferty and Kuris (1996) have estimated that the potential losses due to green crab predation on commercial fisheries species in the United States could be as high as $44 million per year. A wide range of commercial bivalves species along western North American coast are clearly at risk (Jamieson et al. 1998). Also recent work has shown that green crabs pose a significant risk to juvenile Dungeness crabs (McDonald et al. 2001) and may reduce recruitment of these juveniles to the adult populations.

In eastern North America, green crabs have been shown to significantly reduce populations of commercial shellfish species including soft shell clams, *Mya arenaria* (Glude 1955, Ropes 1968), scallops, *Argopecten irradians* (Morgan et al. 1980, Tettlebach 1986), and quahogs or hard clams, *Mercenaria mercenaria* (Walton, unpubl. data). Native, non-commercial species in New England have also been shown to be significantly reduced by green crab predation (Menge 1983, 1985).

The impacts of green crabs in the native range and other introduced ranges are also well documented. Predation by green crabs is considered an important source of mortality for many different commercial species, including blue mussels, *Mytilus edulis*, (Ebling et al. 1964, Dare & Edwards 1976), quahogs, *Mercenaria mercenaria* , Pacific oysters *Crassostrea gigas* in Britain (e.g., Walne 1970, 1977, Davies et al. 1980), flat oysters, *Ostrea edulis*, in France (Marin et al. 1973), and palourdes, *Tapes decussatus*, in Portugal (Vilela 1950). Green crabs have also been shown to have a strong influence on populations of non-commercial species as well such as clams, mussels, and polychaetes in the native European range (Ebling et al. 1964, Dare & Edwards 1976, Reise 1978, Davies et al. 1980, Dare et al. 1983, Reise 1985, Jensen & Jensen 1985).

The large body of data on four different continents provides compelling evidence for significant impacts that *Carcinus maenas* can fundamentally alter marine communities. Importantly, there is a great deal of consistency in the effects reported throughout the native and introduced range of this crab:

- For non-commercial prey species, large effects that often include population declines are attributed to predation by *C. maenas*
- For commercial and aquaculture species, similar effects (high mortality rates and reduced yields) are attributed to *C. maenas*, representing significant economic losses
- Such strong direct effects are believed to result in many indirect effects on invertebrate and vertebrate species including the commercially important Dungeness crab and ecologically sensitive shorebirds.

A Model Management Plan for Future Invasions

The management plan we have developed, in addition to providing a coordinated and coherent plan for managing the green crab invasion, represents an important model system for developing and testing methods and policies that may be applicable to other marine nuisance species invasions in the future.

First, the management structure we develop includes identifying working groups for each task area a) Prevention and Containment, b) Detection and Forecasting, c) Eradication, Control, and Mitigation, and d) Information Access and Data Management We feel this permits the most efficient development of tasks and action plans within existing resource constraints and time. We then outline the a plan for the integration of these groups with the data and information management workgroup to coordinate, archive and make available all the information produced by the other workgroups. This linkage will also act as the contact point for a network of individuals and entities that would need to be part an early detection network. This network would not only be able to quickly identify a new invasion or a range expansion of a current invader such as the green crab, but would also form the foundation for a rapid response effort to implement appropriate eradication or control measures.

Second, this management plan outlines methods including a decision tree for guiding the use of various eradication, control, and mitigation methods that, while somewhat specific for particular species such as green crabs, provide a test of a process that will be applicable to other ANS. In short, we envision development and implementation of a complete system for "early warning – rapid response", as called for in the Management Plan of the National Invasive Species Council and a recent study by the General Accounting Office.

It is important to point out that the earlier belief that eradication was "not possible" in a marine environment is now clearly false. There are at least three good examples of successful eradication of newly established invasions where total eradication has been or is being accomplished. The sabellid polychaete parasite of abalone, *Terebrasabella heterouncinata*, which had been found in natural snail populations adjacent to an abalone hatchery facility in southern California (see Kuris and Culver 1999), was eradicated by hand collection of the snail hosts. The invasive mussel, *Mytilopsis sallei*, was also rapidly and completely eradicated from a single invasion site in a southern Australian harbor (Bax 1999, Willan et al. 2000). Finally, the invasive algae, *Caulerpa taxifolia*, which has invaded two sites in Southern California (Jousson et al. 2000, Williams and Grosholz 2002, *in press*) has been reduced by more than 90% at both sites and is likely to be entirely eradicated in the near future.

This plan includes methods that may be useful the eradication or control of newly established populations created by unusual range extension events in southeastern Alaska or southern California where recruitment from the other populations may be sufficiently limited. Even where eradication or control is not possible, such as in the middle of the current range of the of the green crab, there are demonstrated methods that have been shown to locally mitigate the impacts of green crabs on commercial species (Grosholz et al. 2002) that may be useful in other contexts.

2. Management Options: Prevention and Containment

The purpose of this section is to provide a detailed description of the priority activities that should be undertaken as soon as possible to prevent further spread of the green crab via a comprehensive program aimed at minimizing the spread of green crabs through a variety of mechanisms. This section provides information necessary for several of the other sections including detection and control and eradication.

The goals of this section fall into two broad areas. The first area involves identifying pathways of invasion and qualitatively assessing the risk of that particular pathway. The second area involves identifying management options available for reducing the risk associated with that pathway. In that section, we discuss the types of information needed to accomplish this as well as the strategies that should be most effective.

Pathway Analysis

The first step is to conduct a pathway analysis, and if sufficient data exist to complete a quantitative risk analysis. Begin by exhaustively considering the numbers and types of pathways by which green crabs can likely move or which could facilitate green crab movements. The first most likely mechanism is the spread of ballast water. Other likely human-mediated pathways include: 1) movement of juvenile green crabs with shipments of oysters, clams, mussels and other shellfish*, 2) release of live bait*, 3) movement with harbor-based crab traps, 4) escape from research and education facilities, 5) movement with marine construction equipment, 6) movement of sediments and sands, 7) historical invasions (oyster trade, aquaculture). * <u>and the materials they are packed in</u>.

The second step is to assess the “risk” of future introductions associated with that pathway. This can be accomplished in part or all through the following mechanisms. First, search the literature to determine what is known about the pathway of introduction for invaders at a given site where possible. Second, determine the number and quantity of species being possessed, sold, or distributed by a given industry, user group or other vector where possible. Third, survey industry, consumer groups, hobbyists, etc. to determine awareness of pathway frequency and potential for escape. Fourth, survey industry to determine industry practices regarding disposal of aquarium/pet and bait products, research/education materials, cleaning of construction materials and equipment, screening/quarantine of aquaculture materials.

Management Options

The third step is to evaluate management options for each pathway that reduces “risk” of future introductions. These various options have greater or lesser value in minimizing the risk of spread as well as greater or lesser utility depending on the number of other user groups that are negatively impacted by the management option. Each list of options are ranked in terms of their effectiveness (1 is generally lowest) and their ease of implementation (1 is generally highest). The rankings are nothing more than qualitative rankings of different management strategies, and are not meant to be mutually exclusive options.

Prevention: Pathway Management

Finally, an implementation plan must be developed for the prevention activities listed with each pathway. The plan must include a decision process that will guide the choice of prevention actions and identify persons, agencies, and responsibilities associated with that action. Broadly outlined, this implementation plan would be pathway specific and involve consideration of all prevention actions listed under the specific pathway. The timetable for decisions regarding the choice of prevention action as well as the timetable for the implementation of the chosen action must be made explicit. Also, there should be previously agreed upon criteria upon which to base the decision about which prevention action should be used. These criteria will necessarily change over time as new technology comes available (e.g. new ballast treatments) or as the importance of other pathways changes with new data. Given the current absence of data for most pathways, the most restrictive actions will difficult to justify, so there is an important need to include and educate the affected industries about their role in the prevention process. In general, if less restrictive actions are found to be inadequately prevent movement of ANS, then the next more restrictive action should be undertaken.

Education and outreach to raise public awareness should be a cornerstone for all prevention programs. Activities that develop public awareness must include both industries involved in the sales and transport of ANS but also must include the public at large. Voluntary codes of practice that are pathway and industry specific need to be developed and industries need to be made aware of these codes through workshops, industry trade groups, etc. Industry compliance should be encouraged through economic or other incentives such as environmental value-based labeling of products or services.. Codes of consumer behavior should also be developed and encouraged through distribution of education materials, workshops, etc. Industry must be encouraged to educate their own consumer base, since they can provide information to their own clientele much more cost effectively. In sum, there has to be increased awareness of the problem both within the industry and the public at large and both need to understand that their own business or consumer practices can be a large part of the solution.

Broad Scale Benefits

Although the primary focus of prevention is spread of the green crab, it is clear that pathways are often shared by many species. For example, oyster importation or ballast water discharge is a source (pathway) for scores of invasions. Thus, efforts to highlight and manage pathways for green crab spread are likely to yield many additional benefits, through the interception/reduction of other species associated with the same pathways.

Table 1. Invasion Pathways and Prevention Options

DISPERSAL PATHWAY	PREVENTION ACTIONS
Ballast Water	offshore ballast exchange on-site ballast treatment, onshore treatment (future)
Movement of Commercial Shellfish/Aquaculture Products	inspect aquaculture products for shipping inspect wholesale/retail products require cleaning/sterilization of products prior to shipping quarantine products after shipping restrict shipping
Bait Releases	inspect bait shops and bait buckets require disposal of live bait restrict sales/transportation of nonnative bait
Traps and Cages	inspect traps, cages, ropes require cleaning/sterilizing traps, cages, ropes require disposal of fouling organisms
Research/Education Facilities	Inspection of research/education facilities and suppliers require quarantined facilities for research/education facilities and suppliers require disposal of research/teaching materials
Marine Construction Equipment	inspect equipment require cleaning of equipment require disposal of exotic organisms
Movement of Sediments/Sands	inspect materials require screening/sterilizing materials require disposal of exotic organisms
Historical Vectors	post-hoc evaluation make sure practices are no longer followed

Implementation – Prevention and Containment

Phase 1.

1. Identify the most important pathways of invasion (see Table 1)
2. Develop a pathway analysis to assess the risk involved for each pathway.
3. Identify key points along pathways where interventions can effectively reduce risk of new invasions.
4. Develop a contact network involving members of industries involved with spread (shellfish growers, live seafood distributors, bait dealers), regulatory agencies, tribes and other concerns.
5. Outline a strategy of education and outreach to compliment contact points and persons involved with intervention.

Phase 2

1. Implement pathway controls at key points along identified high priority invasion pathways.
2. Implement education programs targeted towards those associated with industries potentially with spread (as above).
3. Implement education programs designed for a broad segment of the general population.
4. Coordinate with information/data management workgroup to archive and disseminate information

3. Detection and Forecasting

The purpose of this section is to provide a detailed description of priority activities to be undertaken as soon as possible to implement a comprehensive program to detect new invasions and range expansions of the European green crab and to forecast population irruptions in invaded sites. This section provides information necessary for several of the other sections including prevention and control.

The goals of this section fall into two categories. The first goal is to outline specific procedures for detecting the presence of young juvenile green crabs in previously **uninvaded** areas. This detection program will provide an "early warning" of new invasions and provide additional time for restricting activities that would potentially further spread. It would also allow time to develop local education/outreach efforts or other activities aimed at heightening public awareness in order to minimizing the probability of unintentional movement of green crabs.

The second goal is to track the approximate abundances of green crab populations in previously **invaded** areas to allow forecasting of “outbreak” years. The ecological and economic impacts of green crabs are directly related to their abundance, so if outbreak years can be forecasted, this would provide an important warning for resource managers, production fisheries, aquaculture, and others that may be negatively affected by a large year class of green crabs. This would also provide additional time to jumpstart necessary management activities, and increase education and outreach efforts that might ameliorate the impacts of these species in years of high abundance.

Several methods have been developed regarding the detection and forecasting of new invasions, range expansions, and population increases for the European green crab. These methods fall under two main categories. The first category involves methods to monitor **uninvaded** areas to detect new invasions and range expansions. This is most effectively accomplished by detecting the presence of postlarval green crabs and/or the presence of young-of-the-year (YOY) juvenile green crabs. To detect the presence of green crab postlarvae involves biweekly to monthly sampling between April and June. Postlarvae can be sampled by deploying bag collectors attached to docks, moorings, buoys at replicate sites in harbors and bays of interest. Bags are exchanged at the desired interval, collected organisms are rinsed off the collectors, sorted, preserved, and counted. Young-of-the-year (YOY) juvenile green crabs are best sampled by deploying baited minnow traps in intertidal areas at replicate sites in harbors and bays in August and September.

The second category involves monitoring **invaded** areas to forecast “outbreak” years. This is most effectively accomplished through monitoring the abundance of postlarval green crabs, juvenile, as well as adult crab populations. The abundances of green crab postlarvae should be monitored annually between April and June using methods as above. The abundance of young-of-the-year (YOY) juvenile green crabs should also be monitored annually in August and September using the methods described in the previous section. Monitoring adult green crab requires measuring the abundance of adult green crabs using baited traps on an annual basis during July-August.

Outbreak years may also be forecast by physical oceanographic features such as sea surface temperature, wind stress or other remotely sensed data that are predictors of upwelling strength and similar processes that may influence recruitment variability (see Lundquist 2000). Physical proxies such as these have been used to predict population dynamics of other crab species such as the Dungeness crab (McConnaughey et al 1994, Wing et al. 1995, Wing et al. 1997, Lundquist 2000) and have also proved informative for green crabs. For example, wind stress as a measure of upwelling intensity has shown a significant negative correlation with recruitment of young-of-the-year juvenile green crabs.

Outbreaks occur on both the Pacific and Atlantic coast, resulting in severe impacts on native communities and commercial shellfish (see Appendix 1). Measurement of outbreak dynamics on each coast would yield a robust understanding and predictive ability. The ability to predict and track outbreaks allows for mitigation activities by aquaculturists. More broadly, such ability to predict dynamics and impacts of invasions is a fundamental gap in both basic and applied invasion science.

Coupled with this approach is the need for education and outreach to engage fishers, aquaculturists, associated industries, and segments of the public involved with coastal recreation or related activities. Not only should these various interest groups be made increasingly aware of the progress of the green crab invasion, but many of these groups can also become involved with either casual or formal monitoring of new occurrences of green crabs or recording unusually high recruitment of YOY green crabs. Information must be distributed to these groups to educate them about existing problems surrounding green crabs and other ANS and provided information what to look for in an outbreak year. Solicitations to become involved with volunteer monitoring programs should also be made concurrently with education mailings to try to expand the successful results of existing volunteer programs. Efforts to encourage a broad-based public detection capacity must be coupled with a well-advertised and accessible reporting number, as well as the resources to follow up on credible reports.

Contacts at the state and regional level are provided below:

National
ANSTF Green Crab Committee

Regional
WRP Paul Heimowitz, Ted Grosholz
PSMFC Stephen Phillips
ASMFC -New director
ERP formed
MARP to be formed

States/Provinces
(A) Pacific Coast
CA: CDFG Susan Ellis
OR: ODFW (Larry Cooper)
WA: WDFW Scott Smith
BC: Canada DFO Glenn Jamieson
AK: ADFG Bob Piorkowski

(B) Atlantic Coast
ME: Umaine Brian Beal

MA: State Bill Walton
NJ: Rutgers Univ Ken Able
RI-VA: SERC Greg Ruiz

The following network of sites (sites with asterisks ** have established populations) would represent a comprehensive combination of both invaded and uninvaded sites. We list these by state:

California: Morro Bay, Elkhorn Slough**, San Francisco Bay**, Bodega Bay**, Humboldt Bay**
Oregon: Coos Bay **, Yaquina Bay**, Tillamook Bay**
Washington: Willapa Bay**, Gray's Harbor**, Hood Canal, Padilla Bay, Westcott Bay
British Columbia: Useless Inlet (Bamfield), Lemmens Inlet (Tofino), Ladysmith Harbor (Courtney)
Alaska: Copper River/Cordova, Kachemak Bay, Sitka/Juneau
Maine: Wells Reserve

Implementation – Detection and Forecasting

Phase I

1. Develop a contact network of university researchers, agency scientists, fishers and related industry members who can contribute to the network for invasion detection
2. Implement standardized protocol of trapping, sampling and other methods designed to detect new invasions and forecasts changes in existing invasions.
3. Develop methods for using oceanographic and atmospheric proxies to forecast spreading and range expansion events.
4. Link with NOAA National Estuarine Research Reserve sites (NERRs) and other local and national programs to expand network capacity and to increase understanding of factors contributing to outbreak years

Phase II

1. Link the output of the contact network with the information network inked into the information network, or with volunteers
2. Coordinate with information/data management workgroup to archive data and to disseminate information to other groups.

Phase III

1. Coordinate with eradication/control/mitigation group to develop a "trigger" mechanism for implementing decision tree and available options developed with demonstration project

4. Eradication, Control and Mitigation

Decisions on whether or not to attempt to eradicate or control a given population of green crab or merely mitigate for detrimental effects must necessarily be based on the data collected in the detection and forecasting section outlined above. A decision tree (Figure 1) approach is proposed based on knowledge gained about population abundance and the tools currently available for achieving control. Just as crab abundance differs by location, so too may the tools available for controlling the population be different.

Population small with no local recruitment
Eradication (selective harvest, chemical control, biological control, genetic control)
Population established with local recruitment
Control and containment (selective harvest, chemical control, biological control, genetic control)
Population well established, management not addressed
Mitigation
Information from the field-based network of sites, as described above (see Detection & Forecasting), will be used to establish an "early warning system", providing information about the site-specific status of green crab populations. This, in turn, will be used to "trigger" particular actions, outlined by a decision tree and implemented by a rapid response system, developed in this section. Possible actions are discussed briefly below.

A. Eradication

Eradication is most likely to be successful for small newly founded populations of green crab (Myers et al. 2000). Although complete eradication is often considered difficult, there are a growing number of successes with well-established populations (Bax 1999, Culver and Kuris 2000). With a well-designed monitoring program (as above) early detection of new invasions may permit successful **rapid response** and extirpation at a local level. Since green crab populations have been shown to expand and contract in response to successful larval dispersal and recruitment (Berrill 1982, Dries and Adelung 1982), it is likely that eradication would be most feasible near the ends of the species range on both coasts or in very small isolated bays or estuaries. Good examples and candidates for such efforts would be the small population of crabs found in Washington State and Vancouver Island, British Columbia, Canada.

Removal of local populations would be an iterative process, instituted as part of a rapid response plan that detects newly established individuals. Physical removal (e.g. extensive trapping) is the most attractive approach because it avoids unwanted impacts to non-target species, yet all of the methods outlined under regional control and containment (below) should be considered. Such a plan could probably be most rapidly implemented with volunteer groups working directly with resource managers and researchers, who would provide permits, training and oversight.

B. Regional Control/Containment

Once the green crab has become established and natural reproduction is documented to occur on a regular basis, it may be difficult to rapidly eradicate from an area (as noted above), but still very desirable to achieve local or regional control. This may be to contain natural spread (i.e. prevent larval dispersal to an even broader area) or to reduce numbers to a level below which environmental factors such as climate or predation by other species help control populations and where economic and environmental damage does not occur. Although a variety of measures have been used to reduce local impacts of crab predators including green crab on bivalve aquaculture crops (see Mitigation section below), the efficacy of methods used to reduce green crab population abundance on relatively large scales has rarely been evaluated and is uncertain (Yamada 2001).

Selective Harvest. Selective harvest using traps is the easiest initial control method to pursue because it has few environmental constraints (e.g. timing to avoid capture and release of all other non-target animals) and requires little up-front research to implement. Targeted trapping efforts have been used to reduce green crab predation on commercial bivalves in small ponds and embayments (e.g. Martha's Vineyard, Massachusetts, Walton 2000). There is also some evidence that the green crab population in Portugal declined recently due to harvest in a commercial fishery (Gomes 1991). Scale, however, remains an issue because trapping is only economically feasible on a large scale when there is an incentive to fish. Incentives could be either development of a commercial market for crab (bait, food) or a bounty system. Creating an incentive to market or sell an ANS where none formerly existed is a problematic issue and not recommended by this committee because it increases the risk of introduction into new areas and re-introduction into areas where the ANS currently exists. Bait markets tend to be relatively small and easily saturated and also pose a very real potential for re-introducing the problem, unless there is a restriction on marketing live bait. On the east coast both a bait market and a bounty system have been tested to reduce green crab populations and proved largely ineffective (Walton, pers. comm.) For these reasons managers on the west coast are extremely hesitant to allow a commercial fishery to develop. Setting a bounty is difficult because the monetary value must be just enough to create an incentive to fish. This incentive also fluctuates with the abundance of the target species and fishers lose interest when abundance is relatively low, unless the bounty is substantially raised (Walton, pers. comm). Fishing derbies and other "pay-the-public" activities are not recommended as a management tool because they will likely prove ineffective for similar reasons. Non-commercial selective harvest therefore seems most feasible for relatively small contained areas and should be tested in small estuaries along the west coast (e.g. Netarts Bay, Oregon, or Tomales Bay, California).

Chemical Control. Both aerial pesticide application and the use of poison baits have been suggested as means of using chemicals to control green crab. The pesticide carbaryl is currently used to control burrowing shrimp on private oyster beds in Willapa Bay and Grays Harbor in Washington State (Feldman et al. 2000, WDF and WDOE 1992). Carbaryl would likely be very effective for green crab since it is targeted at arthropods and kills other crabs present on the oyster beds. Carbaryl use has been banned in other states however, and its use has not been recommended as a course of action in Washington because green crab are most abundant in the salt marsh and have not been killed via carbaryl spray in oyster beds (Smith 1998). Broad scale use of a chemical to control green crab in other areas would require substantial study of impacts to non-target species and environmental review. Also in view of the recent of the recent Talent Irrigation District decision by the 9th Circuit Court, the use of pesticide application would require an NPDES permit, which might restrict its use in this application. Attempts have been made to use poison bait to control green crab on the East coast in the past with some success (Hanks 1961). The chemicals used however, were more toxic than those that might be evaluated now. The use of poison bait has the advantage of only targeting those animals that are attracted to the bait and would therefore be potentially easier to obtain permits for than aerial pesticide application, but would still involve a substantial environmental review process.

Biological Control. A strong rationale has been developed for exploring the feasibility of biological control as a potential management option for marine pests, and especially green crab (Lafferty and Kuris 1996, Kuris 1997). Lafferty and Kuris (1996) are currently examining the feasibility of using the parasitic barnacle *Sacculini carcini* (which infects and castrates green crabs in northern Europe) as a control agent. Key issues surrounding the use of biological control agents include specificity of the control agent (i.e. does it infect other organisms like the Dungeness crab), efficacy of the control agent for the target species (i.e. does it have the potential to reduce the pest population to a desirable level), and cost including up-front research expenditures. Unfortunately, their results showed that *S. carcini* readily infected native crabs, so their uses as a biological control agent are now in question (K. Lafferty and A. Kuris, unpubl. data). While a biological control agent is not immediately available and will require careful planning, continued support is necessary to insure that research makes this an available option in the future.

Genetic and Molecular Control. A number of genetic and molecular based techniques (e.g. ploidy manipulation, release of sterile males, immuno-contraception) have been used to control pests in freshwater and terrestrial systems (Myers et al. 2000). Australian researchers are now also investigating the possibility of genetically engineering an “inducible fatality” gene that could be introduced into invading populations (Grewe 1997). These techniques all represent emerging technologies and are, at best, in the early stages of development for marine organisms and therefore many years from field application, but like biological control agents, require continued research support to make them available in the future. An advisory panel would

C. Mitigation

Mitigation is the final step in the decision tree where the invasion has proceeded to the point that achieving population control on a broad scale is either perceived to be insurmountable or at least is not presently being addressed. Mitigative control measures may also be used in concert with broader regional scale or local control.

A wide variety of management tools have been tested and used to reduce the effects of predatory crabs on cultured bivalve molluscs including covering plots with predator netting, changing the timing of planting seed, increasing seed size and density, modifying the substrate, and placing the seed in bags, cages, or on racks (Castagna and Kraueter 1977, Eldridge et al. 1979, Kraueter and Castagna 1980, Arnold, 1984, Walker 1984, Eggleston et al. 1992, Toba et al. 1992, Peterson et al. 1995). Some studies have been conducted and used to successfully reduce predation by green crab on bivalves in Europe and along the east coast of North America (Smith 1954, Walne and Dean 1972, Dare and Edwards 1976, Procter 1997, Beal 1998), and recent efforts in California suggest that changing timing of clam seed placement into bags may reduce the impact of green crab larvae that settle into the bags in early spring (Grosholz, pers. comm.).

Cooperative research should continue to proceed on the seasonal dynamics of green crab recruitment and predation in each region, and field tests on the efficacy of various mitigation measures should be conducted in those areas where green crab are abundant.

Implementation – Eradication, Control, & Mitigation

Phase I

1. Gather information and identify which options will be most effective for a given invasion
2. Utilize external advisory panel to assess availability and feasibility of molecular and genetic control methods
3. Develop a decision tree for eradication, control and mitigation outlining the best available options for each decision point
4. For each option, identify the budget needed, the entities responsible for implementing the option

Phase II

1. Test high priority options with a demonstration project at a new or existing site with low abundance, where methods may be able to have a measurable impact.
2. Coordinate with information/data management workgroup to archive data and to disseminate information to other groups.

Phase III

1. Coordinate with detection group to develop a “trigger” mechanism for implementing decision tree and available options developed with demonstration project

5. Information Access and Data Management

Rationale

A key element of this management plan involves clear communication and ready access to information across the diverse range of activities outlined herein. In short, a well-developed communication structure is critical to every aspect of this management plan. This section addresses the information management needed to successfully implement coordinated activities and to make the status of each component of the plan accessible to interested parties.

Objectives

The overall objective for this component of the management plan is to provide the information source(s) and data management needed to efficiently implement the national management plan, providing up-to-date data on protocols, activities, and results to all interested parties. Importantly, this component should meet information needs for research, management, policy, and the general public (including public education and outreach) associated with this plan.

The specific objectives for the Information Management and Access component of the plan are:

1. To provide current information on the research and management activities being conducted under the plan;
2. To describe standardized research and management protocols that allow others to participate and contribute to full implementation of the plan;
3. To sustain a current synthesis of regional, national, and international results in the areas of research and management activities;
4. To create a directory of relevant contacts, activities, and information in support of the plan at the local, state, and regional levels;

5. To develop educational outreach components in support of the plan;

Approach

Three elements are developed in the Management Plan to meet these specific objectives, including (1) a system for information management and dissemination, (2) an advisory committee to guide development of the information system, and (3) a core group of scientists to provide syntheses of current research and management information. Each of these elements is described in more detail below.

A. Information Systems

As the primary information system, the Management Plan calls for the development of an information clearinghouse (hereafter Green Crab Information Clearinghouse), which is composed of a series of electronic databases that are accessible via the World Wide Web. An information database will be developed to meet each of the objectives, and access through the web will provide a comprehensive source of information about green crabs and the management plan that is readily accessible to a wide audience.

More specifically, to address the objectives (above), the clearinghouse website will include the following:

1. A searchable directory of research and management activities focused on green crabs.
2. Standardized protocols for research and management activities under the Management Plan.
3. A database of research and management results obtained under the Management Plan, and regular reports of research and management results, providing a mechanism for tracking and synthesis of results.
4. List of key contacts, activities, and information associated with implementation and coordination of the Management Plan at the local, state, and national level, including point of contact(s) to resolve issues or general queries.
5. A comprehensive and searchable bibliographic database of published papers and reports on all aspects of green crab biology, ecology, and management.
6. An archive of images, data graphics, distribution maps for use as education and outreach materials, as well as links to websites (e.g., Sea Grant) with additional information and outreach materials about green crabs.

We propose to develop and maintain the Green Crab Information Clearinghouse at the Smithsonian Environmental Research Center (SERC), in parallel with the National Ballast Water Information Clearinghouse. The latter was created by the National Invasive Species Act of 1996 (NISA) to analyze and make available national data on ballast water delivery and management patterns as well as invasion patterns and rates. Creating and maintaining a web-based clearinghouse for green crabs at SERC, in conjunction with other such databases that presently exist (see below), will provide considerable savings in resources and take advantage of existing expertise.

B. Advisory Committee

An Advisory Committee will be formed as part of the Green Crab Management Plan to guide the development and implementation of the Information System. The Advisory Committee will consist of scientists, resource managers, and education specialists. Membership of the committee will initially consist of the committee members for the existing Green Crab Workgroup. The Advisory Committee is one of the components of the overall management structure for the overall Management Plan (see section entitled Overall Management Plan Structure & Implementation).

C. Data Analysis & Synthesis

For each of the research and management activities of the Management Plan (e.g., Prevention, Detection/Forecasting, and Control/Eradication), we anticipate a need for data management, synthesis, and interpretation. The Green Crab Information Clearinghouse will serve both as a catalyst for this function and a central source of current information. More specifically, the Clearinghouse would develop and implement databases for each data stream and provide a conduit for information updates.

For each data stream generated under the plan, the Clearinghouse would develop in consultation with the respective research and management groups a centralized database archive. We envision the following step-wise approach to data management and analysis:

1. Data would be submitted by participants in the respective activities, involving a network of researchers/managers and sites;
2. Access to the raw data would be restricted;
3. Analysis and synthesis documents, including publications, would be initiated by those individuals or groups who collected the respective data;
4. Synthesis documents and updates would be posted on the Clearinghouse website for distribution.

Under this scheme, the individual groups (e.g., Detection & Forecasting Workgroup, Prevention Workgroup, Control & Eradication Workgroup) would have sole access to the data for a specified period of time, allowing publication and analysis by the group. An annual report would be generated for each group, allowing the public access to current status, trends, activities, and progress under the various areas of the Management Plan.

To implement this approach, each group outlined in sections I through III of the Management Plan will assist in the database and information management design. Furthermore, each group will provide standardized protocols, key contacts, and regular updates as outlined above.

D. Education and Outreach

In addition to continued delivery of educational programs and materials (both focused on green crab and general aquatic invasive species) and new web-based resources available through the Green Crab Information Clearinghouse, additional education products are likely needed to support the plan. An inventory of existing green crab education materials should be developed and used to identify gaps within particular regions. This needs assessment can also help identify important regional audiences that are currently under-served.

Additional tools that can enhance outreach programs include:

1. Portable specimen displays that can be used to educate volunteers and others regarding identification of green crabs vs. native crabs
2. Educational videos that increases awareness of green crab invasions and impacts, including information on identification and reporting of new invasions, control options, and prevention actions.
3. Electronic and 35 mm slide shows and associated scripts that can be used for presentations to the general public and groups representing particular pathways (e.g., aquaculture industry).
4. "Wanted" posters for areas where green crab infestations have not yet occurred but are anticipated

Current Status

Two elements of the web-based information system have already been developed at SERC, including:

- A searchable annotated bibliography of 1400 publications and reports on green crabs.
- A directory of invasion research on an international scale that is now rapidly expanding and includes some current green crab research projects.

Additional educational and outreach elements have been developed by various Sea Grant programs, and many of these are available on the respective websites.

Implementation

Implementation includes multiple phases of initiation and recurrent activities. Below, we have outlined an implementation plan for the Information Management and Access component of the Management Plan.

Phase I

1. In the first phase, we can quickly establish the Green Crab Information Clearinghouse and include the following elements: Searchable, web-based directory of research and management activities for green crab. This is simply requires slight modification to the Aquatic Invasion Research Directory (AIRD) that already exists at SERC, as described above. Comprehensive and searchable bibliographic database of published papers and reports on all aspects of green crab biology, ecology, and management. This too already exists and simply needs to be placed on the website.
2. Establish web-based links to existing programs and educational materials, including especially those that exist through Sea Grant programs of various states.
3. Establish Advisory Committee (see also next section).
4. Establish Prevention Workgroup, Detection & Forecasting Workgroup, and Control & Eradication Workgroup.
5. Post Management Plan on website.
6. Inventory existing outreach resources and identify gaps/audience needs

Phase II

1. Workgroups provide (a) standardized protocols and (b) schedule of activities for their respective areas of the Management Plan.
2. Workgroups provide list of key contacts, activities, and information associated with implementation and coordination of the Management Plan at the local, state, and national level, including point of contact(s) to resolve issues or general queries.
3. Workgroups advise on the development and implementation of database archive at the Green Crab Information Clearinghouse.
4. Archive of images, data graphics, and distribution maps established on Clearinghouse website.
5. Develop regional versions of videos, displays, slide shows, and other outreach products based on needs assessment. Commit sufficient staff (via Extension system, state agencies, etc.) to deliver outreach programs on an annual basis to targeted audiences.

Phase III (Recurring)

1. Semi-annual meeting of Advisory Committee with advice to Clearinghouse.
2. Semi-annual meeting of Workgroups with advice to Clearinghouse.
3. Annual submission of reports by Workgroups to Clearinghouse.
4. On-going submission and analysis of data by Workgroups.
5. On-going updates of AIRD and Bibliographic databases by Clearinghouse.

6. Overall Management Plan Structure & Implementation

Management Structure

Management and implementation of the work outlined in each of the previous sections, presented as a phased sequence of tasks, will be accomplished through a Workgroup for each respective section. A Workgroup will be formed for each of the four main areas: 1) Prevention, 2) Control & Eradication, 3) Detection & Forecasting, 4) Information & Data Management. Each Workgroup will be develop, oversee, and implement the work outlined in the management plan. In essence each Workgroup will serve as the functional unit to advance elements of the Management Plan under the respective topic areas.

Although each Workgroup will focus primarily within the respective topic area, extensive of coordination and communication will exist among Workgroups. This will occur in two primary ways. First, information will be exchanged directly among Workgroups. For example, each Workgroup is expected to provide information and data to the Information & Data Management Workgroup, both as a data archive and central access point for information distribution. Results from the Detection & Forecasting Workgroup will form the basis of an “early warning system” that is communicated directly to the Control & Eradication Workgroup. Second, each Workgroup will communicate to an Advisory Committee, designed to oversee and guide activities across all Workgroups. The Advisory Committee (equivalent to the current Green Crab Committee) would, in turn, communicate and report on a regular basis to the ANS Task Force (see Figure 6.1 for overview).

To guarantee frequent discussion and coordination across Workgroups, the Advisory Committee will be comprised of the members of the respective Workgroups. More specifically, each Workgroup shall have a chair, who is a member of the Advisory Committee. In addition, the Advisory Committee shall include a representative from each NOAA and USFWS, each regional panel of the ANSTF (for those regions where the green crab is present), Native American tribes, and the commercial shellfish industry.

Each Workgroup will be comprised of primary participants for each topic area. For example, the Detection & Forecasting Workgroup would include research scientists and state/federal resource managers with an intent and ability to contribute substantively to the work elements under the Management Plan. Thus, state and regional participation would occur in each Workgroup, as the Management Plan is implemented across a network of sites. Further, it would be incumbent upon the Workgroup chair to be as inclusive as possible.

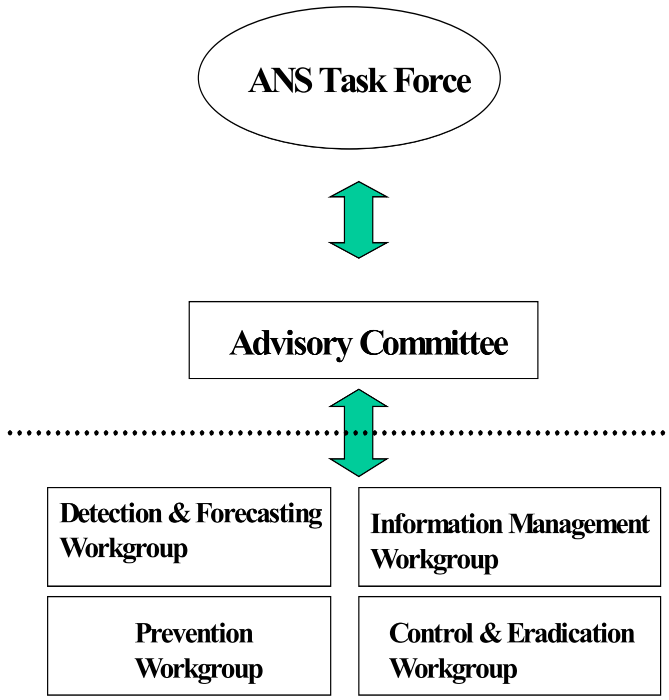

Figure 6.1 Management Structure of Green Crab Management Plan

We recognize education and outreach as a key element to each of the four topic areas and Workgroups. As such, we have not created a separate Workgroup with this purpose. Instead, we recommend that each Workgroup include an education/outreach specialist, to assure clear communication about Management Plan activities to various user groups and identify both needs and opportunities that may exist.

Implementation Plan

The implementation plan, outlined for each task in the four major topic areas (see detailed description in previous chapters), is summarized in this section. For each of the task elements, we have identified (a) possible funding source(s), (b) lead organization(s), and (c) estimated cost (in thousands) by fiscal year. The fiscal years 2002-2010 are divided among three phases, as described earlier.

In some cases, work on particular task elements is already underway or is expected to have no associated costs. This is so indicated by an absence of funding source and/or a specific dollar amount associated with that task; in the latter case, an "X" is used to indicate timeframe for the task.

Although a lead organization is identified for each task, this requires a brief explanation. The lead is not responsible for accomplishing the specific task nor is the funding identified for a particular task dedicated to the lead organization. Instead, the lead organization(s) is responsible for overseeing and organizing the associated activities, as outlined in the Management Plan. For example, UC Davis (Grosholz) would organize the research network for design and implementation of standardized field measures on the Pacific coast under "Detection & Forecasting" . Associated funding would be distributed among participating research groups in the network to defray the cost of supplies, travel, and equipment.

It is important to recognize the cost-effective nature of the implementation plan. For example, the cost of field-based measures @ $75,000/year is extremely low for the quantity and quality of data expected. If we assume a minimum of 10 sites, this amounts to $7,500 per site or research group to support this activity. This is only possible with a considerable amount of "in-kind" support, resulting from contributed effort by research organizations, management agencies, and volunteer groups.

Table Legend:

ADFG – Alaska Department of Fish & Game
ANSTF – Aquatic Nuisance Species Task Force
NERRS – National Estuarine Research Reserve sites
NOAA – National Oceanographic and Atmospheric Administration

PSMFC – Pacific States Marine Fisheries Commission
RCAC – Regional Citizens' Advisory Council of Prince William Sound
SERC – Smithsonian Environmental Research Center
SG – Sea Grant Programs (National and State)
States- State management agencies
UCD – University of California at Davis
USFWS – U.S. Fish & Wildlife Service
WDFW – Washington Department of Fish & Wildlife

A. Prevention and Containment

Task	Fund Source	Task Lead	*PHASE I* FY02	FY03	FY04	*PHASE II* FY05	FY06	*PHASE III* FY07-FY10
Pathway Analysis	USFWS	WDFW, ADFG, SG	15					
Contact Network	---	WDFW, ADFG, SG		X				
Develop Management Strategy	SG	WDFW, ADFG, SG		15				
Implement Management Strategy	States, ANSTF[1], SG	WDFW, ADFG, SG						
(A) Pathway Disruption						100	20	
(B) Education & Outreach						50	25	

[1] ANSTF includes funding for State Management Plans

B. Detection and Forecasting

Task	Fund Source	Task Lead	*PHASE I* FY02	FY03	FY04	*PHASE II* FY05	FY06	*PHASE III* FY07-FY10
Establish Network								
(A) Pacific Coast		UCD	X					
(B) Atlantic Coast		SERC	X					
Standardized Field Measures								
(A) Pacific Coast	RCAC, PSMFC USFWS, WDFW	UCD	X[2]					
	NOAA, NERRs PSMFC	UCD		75	75	75	75	50/yr
(B) Atlantic Coast	SI	SERC	X[2]					
	NOAA, NERRs	SERC		50	50	50	50	50/yr
Develop / Implement Environmental & Forecasting Methods	NOAA , NERRs SeaGrant, NSF	UCD		50	200	75	75/yr	
Contribute to Implementation of Early Warning System (See Below)	---	UCD			X			

[2] Presently funded activity

C. Eradication, Control & Mitigation

Task	Fund Source	Task Lead	*PHASE I* FY02	FY03	FY04	*PHASE II* FY05	FY06	*PHASE III* FY07-FY10
Develop Decision Tree For Rapid Response	NOAA, USFWS	WDFW, ADFG		50				
Demonstration Project(s)	NOAA, USFWS	WDFW, ADFG				100		
Implement Rapid Response & Control Program	NOAA, States, Private Industry	WDFW, ADFG					100	100/yr

D. Information & Data Management

Task	Fund Source	Task Lead	*PHASE I* FY02	FY03	FY04	*PHASE II* FY05	FY06	*PHASE III* FY07-FY10
Establish Information Clearinghouse & Website, including:	USFWS	SERC	30					
(A) Literature Database	SG		X[3]					
(B) Research Directory	USCG		X[3]					
(C) List Key Contacts & Activities								
Maintain Current Information on Workgroup Activities, Results, Protocols, & Links	USFWS	SERC		5	5	5	5	5/yr
Develop/Implement/Sustain Database Archives Images, Maps, & Data Graphics on Website	USFWS	SERC		5	5	5	5	5/yr

[3] Presently funded or completed

Appendix I

A. Distribution & Spread

Geographic Distribution

The green crab is native to Europe, where it occurs abundantly from Norway and the British Isles to the Atlantic coast of southern Spain (Williams 1984). This species has invaded numerous global regions: Australia, North America, South Africa, and possibly Japan (Geller et al. 1997, also see above). The age of these established populations extends from approximately 180 years to 10 years, and the younger populations are still rapidly expanding their ranges. The North American populations represent the two extremes of this spectrum.

The green crab was established in eastern North America before 1817, and spread north and south from New Jersey / New York area, where it was first reported (Say 1817, DeKay 1842, Gould 1841, Almaca 1963, Vermeij 1982; see also review by Williams 1984). It now is well established from Nova Scotia to Maryland, where it is often the most abundant crab in shallow water (Tettlebach 1986, Walton unpubl. data). Although the range of green crabs has been stable along the east coast for many years, the abundance of crabs in the Gulf of Maine appears to fluctuate considerably among years, resulting perhaps from die-offs during severe winters (e.g., Welsch 1968, Elner 1981, Beukema 1991).

The population in western North America became established in San Francisco Bay in 1989-90 and has spread at a rapid rate, predominantly northward along the coast (Cohen and Carlton 1995, Grosholz 1996). The crab successfully invaded the California embayments of Bolinas Lagoon, Tomales Bay, and Bodega Bay in 1993, and these populations have grown exponentially (Grosholz and Ruiz 1995, Grosholz et al. 1998). The crabs arrived in Humboldt Bay, California, in 1995 and appear to be well established (Miller 1996). In 1997, the first green crabs were found in Coos Bay, Oregon, and a total of nine large (54 to 84mm) crabs have been collected to date (Richmond 1998). Despite intensive searching, no additional crabs or young-of-the-year crabs have been discovered. Thus, it's not clear whether a reproductive population is actually established at the Oregon site, or whether the collections to date represent a single, small larval cohort that entered Coos Bay (Neil Richmond, pers comm). The present southern extent of the *Carcinus maenas* range is Elkhorn Slough in Monterey Bay, California, where the crabs have occurred since 1994 (Grosholz 1996, Grosholz & Ruiz unpubl. data).

Unlike the population in eastern North America, the range of green crabs in western North America is still expanding. Expansion has occurred in an episodic fashion, with several years of range stability followed by colonization of one or more new sites, usually to the north (Grosholz & Ruiz 1995, Grosholz

1996). The potential range of this invader is thought to extend from the Gulf of Alaska to Baja California (Cohen et al. 1995).

Mechanisms of Introduction & Spread

Multiple pathways have existed for the introduction of *Carcinus maenas* around the world for centuries, and these have changed over time. The earliest introductions, in eastern North America and mainland Australia, probably resulted from transfer with dry ballast or on the hulls (e.g., especially within interstices of shipworm galleries) of ships arriving directly from Europe. The relative importance of these particular vectors for the transfer of crabs and other organisms appears to have diminished during the 20th century, because of changes in the design and maintenance of ships as well as shipping practices (Carlton 1979, 1989). Hull fouling may still be an important vector for some species (Rainer 1995), but the use of metal hulls and anti-fouling paints has greatly diminished the opportunity for transfer via this pathway. This is especially true for mobile, benthic species, which could previously nestle into wooden hulls.

The recent introductions of green crabs over the past few decades (in western North America, South Africa, and Tasmania) most likely resulted from any combination of transfer mechanisms that are common today:

- <u>Movement in ballast materials of ships</u>. For example, larval and adult decapod crustaceans are present in ballast water of ships (Carlton & Geller 1993, Smith et al. 1996, Ruiz et al. unpubl. data).
- <u>Transfer with aquaculture, fishery, and bait species</u>. Decapods are sometimes associated with aquaculture products sent for grow-out and market, away from source locations (Carlton 1992, Ruiz unpubl. data). Fishery and bait species sent to distant markets can also include decapods associated with packing materials which may be discarded into the environment (Carlton 1992).
- <u>Direct release of crabs obtained as pets, research organisms, or classroom material</u>. This has clearly been a source of invasions for other organisms (e.g., Carlton 1989, Carlton 1992) and could be a vector for crab introduction.

Unlike the two earliest invasions, the mechanism of introduction and source region for more recent invasions is not certain. Although we believe direct release is least likely, each of the above three introduction pathways is possible. Furthermore, with the establishment of each successful invasion, the number of potential source regions increases. For example, the green crab population in California could have come directly from Europe, eastern North America, Australia, or South Africa. Each of these regions has some potential vectors which could transfer green crabs to California. Furthermore, as the number of potential donor regions increases, the opportunity for invasion by both single and multiple events increases. Current research is now underway to decipher the source histories of various green crab invasions throughout the world (Jon Geller, pers. comm.).

For western North America, the rate and extent of range expansion of green crabs may be influenced strongly by human activities. To date, larval dispersal appears to be the primary mechanism for range expansion along western North America (Grosholz & Ruiz 1995, Grosholz 1996). Although the rate of range expansion has been relatively rapid so far, it's not clear whether certain barriers (e.g., distance between embayments, currents) exist which may reduce the rate and potential range of this invader. Human-mediated transfer along the west coast could establish populations outside the present range, such actions would both accelerate the rate of invasion and by-pass any existing barriers (see also Management Options, below). Each of the common transfer mechanisms discussed above exists in western North America and could potentially create this "leapfrog effect" in the green crab invasion. To date, there has not been a formal analysis of these coastwise pathways along western North America to assess (1) the risk of such coastwise dispersal or (2) actions to minimize such risk.

Such coastwise, domestic transport may explain the recent range expansion of green crabs in Australia. Although green crabs became established in Australia nearly 100 years ago, they were only recently reported in the island state of Tasmania, representing a > 80-year delay. Tasmania is separated by some 80 miles from the mainland which apparently represents a substantial barrier for *Carcinus maenas*. It's possible that this barrier was eventually overcome by larval transport across the Bass Straights, requiring an unusual convergence of conditions that had not occurred previously. Alternatively, the recent colonization may have resulted from human-mediated transfer, such as ballast water release, from mainland Australia or elsewhere. We will likely never know which mechanism was responsible for this jump in distribution. Importantly, this barrier between the mainland and Tasmania is one of distance and currents that separate suitable habitats, and the distances are not very great compared to those among bays along western North America.

B. Biology & Ecology

An extensive literature on the biology and ecology exists for *Carcinus maenas*, and we have summarized some of this information in this section (see Table 1). It is important to recognize that most information comes from the native population and, to a lesser extent, from eastern North America (i.e., site of the oldest invasion). Although this provides a good point of reference, there may be some differences between the native and invading populations (e.g., season or timing of reproduction in the southern hemisphere, demography, etc.). These comparative data for invading populations is just now becoming available, and we will discuss some of the apparent similarities and differences that are emerging in current research.

Life History & Population Characteristics

Environmental Tolerance. Green crabs are both eurythermic and euryhaline (Table 1 and references therein). These crabs can survive a range of temperatures from freezing to 30^{o}C, and reproduction is reported from 3-26 ^{o}C. They are also reported to survive in a broad range of salinities, from 1.4 to 54 parts per thousand (ppt), although they are usually found in waters from 10-33 ppt.

Larval stages are less tolerant to extremes in temperature and salinity than postlarval crabs, and successful development generally increases with increasing salinity (Williams 1984, Dawirs 1985). Not surprisingly, temperature and salinity have interactive effects on larval development and survival (Nagaraj 1993).

The distribution of green crabs along eastern North America, and elsewhere, is thought to be limited primarily by temperature (Carlton & Cohen 1998). More specifically, it appears that the temperature required for successful reproduction sets range limits. Nonetheless, because the crab is eurythermal, a potential range of thousands of kilometers often falls within its temperature tolerance.

Life History. *Carcinus maenas* is dioecious and reproduces only by sexual reproduction (Table 1 and references therein). These crabs are iteroparous. Reproduction is limited to a season of 3-4 months. Individual crabs can mate multiple times within a single year, but females probably produce eggs only once per year. The number of eggs per reproductive event varies by female size, and a typical female will produce 185,000 or more eggs/event. Eggs are brooded externally by the female and hatch into plankton larvae after 17-80 days. It takes approximately 90 days for larvae to develop through 4 successive zoeal stages and then metamorphose into benthic-dwelling, postlarval crabs. The length of time required for development depends upon temperature and salinity conditions, as well as food availability.

Although green crabs can reach sexual maturity within one year, this appears to vary among geographic regions. It typically takes 2 years to reach maturity in northern Europe, whereas crabs appear to mature earlier in North America and Australia (Grosholz & Ruiz 1995, unpubl. data). Furthermore, crabs also appear to grow more rapidly and reach a larger size along both coasts of North America and Australia when compared to crabs in the native range (Grosholz & Ruiz 1996, Ruiz et al. 1998, Kuris et al. unpubl. data).

Such differences in demography and size structure may significantly influence the dynamics and impact of invading populations. First, because fecundity is size dependent, increased female size should result in higher egg production per female. Also, earlier age at first reproduction will result in a shorter generation time. Controlling for other factors, both features should contribute to a higher intrinsic rate of population growth, *r*, for invading populations compared to the native population. Thus, such shifts in population characteristics could increase the relative rate of population growth (i.e., local density). This may have important consequences for the rate of geographic spread, if it is density-dependent, as well as the ecological impact of these crabs (see Ecological & Economic Impacts, below).

Community Ecology

Habitat Distribution. As with environmental tolerances, the green crab is able to utilize a broad range of habitat types (Table 1 and references therein). 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. These habitats span a wide range of exposure gradients, from protected embayments to exposed outer coasts.

Despite the wide range of habitats reported for *Carcinus maenas* in Europe and eastern North America, the utilization of rocky habitats appears to be relatively limited in western North America and Tasmania (Grosholz & Ruiz 1996, unpubl. data). For example, green crabs are very common and ecologically important in rocky intertidal communities of eastern North America (Menge 1983, 1995). By contrast, censuses of exposed and some protected rocky shores in California and Tasmania failed to detect any green crabs. Use of sheltered rocky habitat also appears to be uncommon for many locations (although A. Cohen reports some use of some rocky habitats). The reason for this difference in habitat utiilzation among coasts is unclear. Although habitat use is presently most limited for sites of the recent invasion (e.g., California and Tasmania), and it is uncertain wither this will change over time at these sites. If exposed coasts and rocky substrate are unacceptable habitat to the crabs in California and Tasmania, this may affect the pattern and rate of range expansion.

Abundance. Although habitat use by green crabs presently varies among geographic regions (as above), the crabs are consistently abundant in relatively sheltered, soft-sediment habitats. Within its present ranges, *Carcinus maenas* is often the most abundant crab species is soft-sediment bay and estuaries of Europe, Tasmania, and both coasts of North America (Tettlebach 1986, W. Walton unpubl. data, Grosholz et al. 1998, Ruiz et al. 1998). Moreover, comparison of identical trapping efforts suggests that *C. maenas* abundance is similar in soft-sediment bays among these regions (Ruiz et al., unpubl. data). Mainland Australia may be an exception to this pattern (pers. obs., A. Kuris pers. comm.), and we are presently investigating this region.

Prey. Along with its wide range of environmental and habitat tolerances, the green crab exploits a wide range of prey types (Table 1 and references therein). Reported prey includes molluscs (clams and snails), crustaceans, annelids, fish, and algae. Although there is considerable variation in diet among sites, molluscs and crustaceans are numerically often the most abundant prey consumed (Grosholz & Ruiz 1996).

There is strong evidence that predation by *Carcinus maenas* has caused significant declines in molluscan and crustacean prey populations, which include commercial species in North America. It also appears probable that green crabs can have indirect effects on invertebrate, fish, and shorebird populations. (See Ecological and Economic Impacts for review.)

Predators & Parasites. Although it is evident that larval and postlarval green crabs have a variety of predators, from fish and birds to mammals and invertebrates, their effect on crab abundance has not been tested (Table 1 and references therein).

Carcinus maenas is also host to a broad range of parasites and pathogens (Brock & Lightner 1990, Meyers 1990). Interestingly, these are relatively rare (i.e., low prevalence and intensity of infection, and low species diversity) for introduced populations (A. Kuris pers. comm.). Some of these parasites can castrate or kill its green crab host (Brock & Lightner 1990, Meyers 1990, G. Lauckner pers. comm.). While green crabs' parasites could theoretically regulate or control a host population under particular conditions (e.g., Kuris & Lafferty 1992, Lafferty & Kuris 1996, Goggin 1997), such an effect has not yet been demonstrated or adequately tested for *C. maenas.*

C. Ecological & Economic Impacts

Impacts in the Native Range

Carcinus maenas is an important predator in bays and estuaries of Northern Europe, where it can significantly reduce the density of its prey populations. Numerous descriptive and experimental studies indicate heavy predation pressure by green crabs on a variety of invertebrates, from molluscs and polychaetes to crustaceans and nematodes (Scherer & Reise 1981, Reise 1978, 1985, Gee et al. 1985, Jensen & Jensen 1985, Bachelet 1987, Le Calvez 1987, Sanchez-Salazar et al. 1987). Although there is strong support for direct effects of green crab predation on some prey populations, effects on other prey species remain untested. Furthermore, indirect effects on community processes are virtually unexplored. For example, reduction of bivalve or other invertebrate populations can have significant effects on larval recruitment patterns, sediment characteristics, invertebrate community structure, and vertebrate predators (Fager 1964, Rhodes 1974, Peterson & Andre 1980, Santos & Simon 1980). Although researchers suggest the likelihood of such community level effects (e.g., Scherer & Reise 1981, Reise 1985, Jensen & Jensen 1985), measures are not yet available to test for this in the native range.

The direct effects of *Carcinus maenas* predation have been best measured for bivalve mollusc prey populations, some of which are commercially important species. Many studies have documented a high proportion of bivalves in the diet of green crabs as well as significant declines in bivalve prey densities that are attributed to predation by green crabs (e.g., Reise 1978, 1985, Jensen & Jensen 1985).

Predation by green crabs is considered an important source of mortality for many different commercial species, including:

- the blue mussel, *Mytilus edulis*, in Britain (e.g., Ebling et al. 1964, Dare & Edwards 1976);
- the quahog and Pacific oyster, *Mercenaria mercenaria* and *Crassostrea gigas* (respectively), in Britain (e.g., Walne 1970, 1977, Davies et al. 1980);
- the flat oyster, *Ostrea edulis*, in France (Marin et al. 1973);
- the palourdes, *Tapes decussatus*, in Portugal (Vilela 1950).

Although the quality of information on green crab impacts varies among these bivalve species, there are many quantitative measures for some species that indicate significant mortality is caused by green crab predation. For example, the effect of green crabs on blue mussel populations is especially evident. *Carcinus maenas* feed intensively on mussels in field and laboratory experiments and appear responsible for mortality rates of up to 100%. Furthermore, in paired experiments, crab exclusion has resulted in striking increases in survivorship compared to mussels in unprotected plots at the same locations (e.g., Ebling et al. 1964, Dare & Edwards 1976, Davies et al. 1980, Dare et al. 1983; see also discussion of control measures, below).

Despite strong evidence for the direct impact of *Carcinus maenas* on some prey populations, especially bivalve molluscs, there are many aspects of these predator-prey impacts that remain unresolved in the native range. More quantitative and experimental data are clearly required to measure and understand direct impacts on the many target prey populations. Greater experimental effort is also required to better understand the probable indirect effects on population and community processes.

It would be especially instructive to measure both spatial and temporal variation in the magnitude of these impacts. Although green crabs are one of the most conspicuous and abundant predators in soft-sediment habitats of northern Europe, their relative density and impact appears to vary among years (e.g., Welsch 1968, Beukema 1991) and sites (e.g., Walne & Dean 1972, Dare et al.

1983 Raffaelli et al. 1989). This variation can provide valuable insights into the role of these crabs and potential management strategies:

1. Comparing mortality rates and community attributes among years offers opportunities to test for both direct and indirect interactions, using multivariate statistical procedures. For example, Jensen & Jensen (1985) measured the decline of cockles from $33{,}000/m^2$ to $7{,}000/m^2$ within two months, during a year of relatively high crab abundance, and crabs appeared responsible and capable of inflicting this mortality. Following cold winters, crabs are much less abundant, so their effects on prey populations and communities should be reduced (e.g., Beukema). This approach to measuring green crab effects on large spatial scales is only now being explored.
2. Testing for general habitat features that influence the abundance or performance of green crabs provides opportunities to (a) test for direct and indirect effects of predation (as above) and (b) select sites which minimize impacts on mariculture species. For example, spatial variation in crab abundance is evident within and among sites (e.g., bays or estuaries), and this should lead to variation in impacts. As well, the per-capita performance of green crabs varies by habitat characteristics (e.g., sediment grain size; Walne & Dean 1972). The effect of site characteristics on the combination of abundance and performance has not yet been explored to test hypotheses about impacts or to improve mariculture success.

Thus, although the European literature confirms a significant role of *Carcinus maenas* as a predator in benthic communities, there is still very little known about community-level effects or the spatial and temporal pattern of any effects within the native range.

Impacts outside the Native Range

A substantial amount of information is now available, and rapidly emerging, on ecological impacts of *Carcinus maenas* outside of the native range. Extensive historical observations and data exist on impacts for eastern North America, and further research on this topic is underway. In addition, the recent invasions of western North America and Tasmania have been the focus of major research programs to measure ecological impacts.

In many respects, a higher quality of data is emerging to evaluate impacts for the invading populations compared to the native population. This results from two main differences with research in the native range:

- First, invading populations provide an opportunity to compare communities before and after invasions. This allows detection of conspicuous changes on very large spatial and temporal scales, following the addition of the green crab. Removal of these crabs from the native range, to compare effects over similar space and time scales, simply is not feasible.

- Second, recent studies of invading populations appear to be much more quantitative and experimental than previous studies. This reflects a general trend in ecological research over the past few decades, allowing improved interpretation of patterns through controlled manipulations. Although experimental approaches are also now common in Europe, many of the studies on *Carcinus maenas* impacts from the native range were done earlier and rely on uncontrolled experiments.

We review here the available information on impacts for invading populations.

Eastern North America. Green crabs are an important predator in shallow waters of the eastern U.S., where they have significant impacts on soft-sediment and rocky shore communities. The crabs utilize a broad range of prey, and molluscan taxa appear to be preferred when available (Ropes 1968, Elner 1981). As reported within the native range, *Carcinus maenas* in the eastern U.S. has also been associated with significant mortality for numerous bivalve mollusc populations in soft sediments, including:

- Soft shell clams, *Mya arenaria* (Glude 1955, Ropes 1968);
- Scallops, *Argopecten irradians* (Morgan et al. 1980, Tettlebach 1986);
- Quahogs or hard clams, *Mercenaria mercenaria* (Walton, unpubl. data);

It is clear that predation by green crabs is a major source of mortality for each of these species, and available data suggest that production of each fishery may be limited by this predation. Below, we review the existing information for each species, as well as community level impacts for soft-sediment and rocky shores.

a. Soft Shell Clams. For New England, the dramatic decline in landings of the soft shell clam (*Mya arenaria*) earlier this century was associated with a northward range expansion of green crabs (Glude 1955, Ropes 1968). MacPhail et al. (1955) reported mortalities of planted soft shell clams as high as 57% over a 3-day period following the arrival of green crabs, compared to estimated mortalities of ~10% per month. Laboratory feeding experiments demonstrated the capacity of green crabs to eat these and other species of molluscs. Given their observations of relatively high green crab abundances and feeding rates, MacPhail et al. (1955) stated:

> "It must be concluded that the green crab is one of the worst, if not the worst, clam predators we know. Its ability to multiply rapidly, to feed on many varieties of shellfish other than commercial species, and its large appetite for commercially important shellfish, all suggest that it can do enormous damage."

Taken together, these observations suggest the role of *Carcinus maenas* in both increased mortality and decreased harvests of soft shell clams, and demonstrate a causal mechanism (predation) through laboratory feeding experiments and diet analyses.

Although the above observations provide correlative evidence for green crab effects on soft-shell clams, additional caging experiments demonstrated that the threat of predation on planted clams was reduced compared to uncaged control plots (Smith et al. 1995). For one experiment, no clams remained in uncaged plots after 6 months, compared to densities of 33-38 clams/ft^2 in protected plots. Smith et al. (1995) also suggested that predation rates may vary strongly among sites that differ in sediment characteristics. These data provide only a rudimentary sketch of the dynamics between green crabs and soft-shell clams. These dynamics could be better quantified if measurements included spatial and temporal patterns of predation (as above).

b. Scallops. Scallops (*Argopecten irradians*) experience intense predation between August and October which has been attributed primarily to predation by *Carcinus maenas* (Morgan et al. 1980, Tettlebach 1986). In Connecticut, where these studies were conducted, weekly rates of crab predation on scallops were as high as 70%. Green crabs were the most abundant crab predator in censuses and were often observed feeding on scallops in the field. Combined with laboratory feeding experiments, these data suggest that (a) green crabs were responsible for most observed mortality in scallops, (b) scallop populations may be limited by predation pressure from crabs, and (c) scallops achieve a size refuge from green crab predators within their first year.

A similar pattern of green crab predation on scallops is reported for Martha's Vineyard, Massachusetts (P. Bagnall, pers. comm.). Green crab populations are relatively abundant in local ponds (W. Walton, unpubl. data) and are believed to both cause high mortality of scallops and limit this fishery. As a result, a bounty for green crabs was created in an effort to reduce this population and improve the fishery.

Although extensive data already exist for the interactions between green crabs and scallops in Connecticut, our understanding of this predator-prey interaction and the fishery dynamics would benefit from additional experiments on various temporal and spatial scales (as above), including especially large scale crab exclusion experiments.

c. Quahogs. Although little has been published to date concerning impacts of green crab predation on quahogs (*Mercenaria mercenaria*), this is the present focus of a current Ph.D. dissertation (W. Walton, University of Maryland). Past studies have demonstrated relatively high predation rates on quahogs in New England, although green crabs were not a known causal agent (e.g., Flagg and Malouf 1983). On Martha's Vineyard, green crabs are considered the major cause of mortality and poor fishery performance for quahogs, as well as scallops (P. Bagnall, pers. comm.). Using multiple ponds on Martha's Vineyard, Walton's current research demonstrates that (a) green crabs are the most abundant crab predator on quahog beds, (b) green crabs are capable of feeding intensively on and causing observed mortality of quahogs, and (c) mortality of quahogs is significantly reduced in cages that exclude green crabs compared to uncaged plots.

d. Soft-sediment communities. It is increasingly evident that predation by green crabs is having significant direct effects on multiple bivalve populations of eastern North America, but the community-level consequences have not been tested. As mentioned for European communities, it is probable that other prey populations are impacted and that a broad range of strong indirect effects have resulted. However, this broader scope of green crab effects remains to be explored.

e. Rocky shore communities. Both direct and indirect effects of *Carcinus maenas* have been well documented in rocky shore communities of New England (Menge 1983, 1995). Experimental studies have measured a significant negative effect of green crab predation on the abundance of gastropod grazers, and the removal of these grazers has significant indirect effects on the community. Interestingly, coincident with the arrival of *C. maenas*, it appears that some gastropods have undergone morphological evolution in response to increased predation pressure from this crab (Vermeij 1982, Seeley 1986).

Western North America. Although green crabs are only a recent arrival to western North America, a substantial body of information has already accumulated which suggests predation by this crab is already having significant ecological and economic impacts. Since the arrival of green crabs in 1993 to Bodega Bay, California, the abundance of native bivalve molluscs and grapsid shore crabs have declined by 90-95% as the direct result of green crab predation (Grosholz et al. 2000). As observed for other geographic regions, experiments in the lab and field demonstrate that this invader feeds intensively on bivalve molluscs in the laboratory and field, and will significantly reduce the abundance of clam and other invertebrate populations in field enclosures (Cohen et al. 1995, Grosholz & Ruiz 1995). It also preys upon grapsid crabs in laboratory and field experiments (Grosholz et al. 2000). Based upon a 15-year record of invertebrate abundance at one site for Bodega Bay, there are numerous additional changes that coincide with the green crab arrival and the decline of these prey populations (Grosholz et al. 2000, Ruiz 1987). These include rapid change in invertebrate abundances and sediment characteristics, which are interpreted as possible indirect effects of green crab predation. Current experiments are underway to test for indirect effects of green crab predation on these same attributes.

Although rapid changes have occurred in the soft-sediment community that appear to result from green crab predation, there are many additional direct and indirect effects that are predicted. Some of the most conspicuous and testable changes include:

- The commercial Dungeness crab, *Cancer magister*, may experience both intense predation and competition from green crabs. Studies by McDonald et al. (2001) demonstrate the negative impacts of green crabs on juvenile Dungeness crabs in enclosure studies. Additional field experiments suggest that the Dungeness crab is highly vulnerable to predation by green crabs (Grosholz & Ruiz, unpubl. data). Dungeness crabs utilize shallow water bays and estuaries as juvenile crabs, and overlap broadly in both habitat utilization and diet with green crabs (Ruiz 1986, Gunderson et al. 1990). It appears that the juvenile Dungeness crabs may suffer high mortality rates in this habitat due to green crab predation (Grosholz & Ruiz 1995).

- Shorebird populations may experience population declines based on reduced food resources. Previous work indicates a relatively large overlap in diet between various shorebird species and green crabs. In 1985, a significant decline in shorebird abundance and physiological condition was observed with the collapse of food resources in Bodega Bay (Ruiz 1987). It appeared that the near local extinction of the clams *Nutricola* spp., a major food source for many shorebird species, contributed strongly to this decline. These are the same clams, which have declined more recently with the arrival of green crabs.

Changes in invertebrate communities may affect food resources for a variety of other vertebrate and invertebrate taxa which utilize shallow-water bays and estuaries. Recent doctoral studies by R. Estelle have demonstrated direct negative impacts of green crab foraging of subsequent foraging of shorebirds in experimental enclosures (unpub. data). Although these and other potential impacts may occur in individual estuaries with the range expansion and population increase of *Carcinus maenas*, there may also be broadscale regional effects on shorebird and fishery populations. For example, if significant changes in food resources and predation are limited initially to a few bays, other bays may provide important refugia for birds (during winter and migration) and fishery stocks. However, as the green crab population expands and such refugia diminish, a threshold may exist beyond which large-scale regional declines would occur for highly mobile and broadly distributed species.

In addition to predicted effects on the Dungeness crab, some impact on commercial bivalve species appears likely for western North America. Based upon studies of other green crab populations around the world (see other sites discussed in this section), we predict declines in wild stocks and aquaculture species due to crab predation. Finger (1998) has recently reported losses of cultured Manila clams *Venerupis* (=*Ruditapes*) *philippinarum* as high as 50% in Tomales Bay, which he attributes to *Carcinus maenas*. Studies by Grosholz et al. (2002) have shown that altering the growout methods can substantially reduce crab predation. Their work showed that delaying transfer of seed clams to growout bags from spring to late summer significantly reduced the numbers of green crabs recruiting into the growout bags and consequently increased survival to market size.

The impacts of *Carcinus maenas* predation on commercial fisheries may be greatest in areas north of the present range. For example, estuaries in Washington support a much larger Dungeness crab nursery compared to California (Ruiz 1987, Gunderson et al. 1990). In addition, it appears that the region of Washington and British Columbia also support the greatest commercial fishery and aquaculture industry for bivalve molluscs (e.g., Jamieson et al. 1998a, b).

For western North America, it appears that green crabs are presently not impacting rocky shore communities on exposed coasts, and virtually no information exists for more protected rocky shore communities. The crabs have not been reported for exposed rocky shores along western North America, unlike eastern North America. Although this may change over time, the crabs are currently having no impact in this habitat. In contrast, green crabs have been reported for some sheltered rocky habitats in San Francisco Bay, but their possible impacts on this community have not been tested (A. Cohen, pers. comm.).

Tasmania. As in western North America, *Carcinus maenas* exerts heavy predation pressure on native species of bivalve molluscs and crabs in soft-sediment habitats of Tasmania, where it appears to be responsible for significant declines in the abundance of these prey species (Ruiz, Walton, Thresher, Proctor, and Rodriguez unpubl. data; see also Thresher 1997 for abstracts and brief review). The diet of free-ranging green crabs includes primarily bivalves and decapod crustaceans, and green crabs cause significant mortality on two native crabs and multiple bivalve species in field enclosures. Many of these prey populations (the grapsid crab *Paragrapsus gamardii*, the lycosid crab *Philyra laevis*, and a composite of all bivalve species) are significantly more abundant outside the current range of green crabs, compared to invaded regions of Tasmania. In addition, the mortality for seeded clams (*Katylesia* sp.) and mussels (*Mytilus* sp.), as well as tethered crabs (*Paragrapsus gamardii*), is significantly greater within the range of *C. meanas* than outside its present range. These data are consistent with the hypothesis that green crab predation has drastically decreased the abundance of each prey population. We are now testing for such changes at the leading edge of the invasion, using a before-after-control-impact or BACI design (which measures differences over time for sites that become invaded, compared to sites that remain uninvaded).

The impact of *Carcinus maenas* on commercial and aquaculture species in Tasmania is presently unclear. Green crabs feed intensively on the clam *Katylesia* sp., which is now harvested and sold. Although current research suggests an impact on this fishery is likely (as above), this has not been measured or adequately tested to date. Mussel and oyster culture is common in Tasmania, but no impacts have been reported by local industry. However, it is worth noting that much of the aquaculture industry is located outside the current *C. maenas* range. Finally impacts on other fisheries have not been explored.

We predict that indirect effects of *Carcinus maenas* predation (a) exist in the invertebrate community of invaded sites and (b) will also occur for some bird and fish populations that utilize invertebrate food resources (as described above). For example, we predict that the local oystercatcher (*Haematopus longirostris)* population will become food limited as the range of green crabs expands. These birds rely largely on locally abundant bivalve populations for food. As in California, it appears that these bivalves may decline due to crab predation which could thereby impact the bird population (e.g., Ruiz 1987). Similar trophic effects are possible for other vertebrate and invertebrate predators that utilize prey impacted by *C. maenas*.

To date, green crabs are not found on exposed rocky habitat in Tasmania and, therefore, are not having an impact there (G. Ruiz, pers. obs.). They can be found occasionally on and around rocks in sheltered habitats, but any potential effects on this community have not been measured.

South Africa. The available information on impacts of *Carcinus maenas* in South Africa is very limited to date (LeRoux et al. 1990, Griffiths et al. 1992). Although the diet of green crabs is similar to that reported for other global regions, including molluscs and crustaceans, it also includes a relatively large proportion of polychaetes. Based upon these data and reports from the native range, Griffiths et al. (1992) predict that green crabs may have a strong local effect on prey populations and the mariculture industry. However, they also predict few, if any, impacts for the exposed rocky shore community.

Summary of Impacts

The large body of data on four different continents, from field and laboratory experiments to diet analysis and long-term monitoring programs, provide compelling evidence for significant impacts that *Carcinus maenas* can fundamentally alter marine communities. Many of the indirect and community-level impacts are untested, and further work is now needed to clarify these impacts and community interactions. Nonetheless, it appears virtually certain that *C. maenas* has a significant impact on marine communities as well as commercial fisheries. Importantly, there is a great deal of consistency in the effects reported throughout the native and introduced range of this crab:

- For non-commercial prey species, strong and measurable effects that often include population declines are attributed to predation by *C. maenas*;
- For commercial and aquaculture species, similar effects (high mortality rates and reduced yields) are attributed to *C. maenas*, representing significant economic losses;
- Such strong direct effects are believed to result in many indirect effects on invertebrate and vertebrate species, which include those of commercial interest (e.g., the Dungeness crab of western North America).

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