THE IMPACT OF THE EUROPEAN GREEN CRAB (*CARCINUS MAENAS*) ON THE RESTORATION OF THE OLYMPIA OYSTER (*OSTREA LURIDA*) IN TOMALES BAY, CALIFORNIA

by

Caitlin Snyder

Date:________________

Approved:

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Dr. Richard Forward, Advisor

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Dr. William H. Schlesinger, Dean

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Abstract

The introduced European green crab, *Carcinus maenas*, poses a potential risk to the restoration of the native Olympia oyster, *Ostrea lurida*, in Tomales Bay, California. The green crab is a voracious predator, and has negatively impacted shellfish in both its native and invaded environments. The Olympia oyster population in Tomales Bay is low due to pollution, predation, and past overharvesting. A collaborative restoration project began in 1999 to try and reinstate the Olympia oyster to Tomales Bay by placing artificial reefs at several locations in the Bay. I investigated the potential impacts of the European green crab on the Olympia oyster during July and August 2003. At four field sites in Tomales Bay, I trapped green crabs at both potential and established oyster reef restoration areas. I conducted laboratory feeding experiments of *C. maenas* on *O. lurida* to get an idea of whether or not the crabs would consume the oyster, and whether different sizes of crabs showed a preference for varying sizes of oyster. Initial trapping results suggest higher green crab population numbers at rocky habitats as opposed to mud flats. In addition, the trapping data suggest it may be possible to trap out the green crabs from the reef areas. The feeding experiments indicate that the green crabs do consume the Olympia oysters, and that the number of oysters consumed decreased as oyster size increased.

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Introduction

Invasive species are considered to be one of the top threats to biodiversity today. As scientists and managers strive to conserve native ecosystems and their species, invasive species threaten to undermine these efforts. Restoration efforts are becoming more popular as a means to protect not only the biological and physical aspects of an ecosystem, but the cultural as well. The restoration project of the Olympia oyster, *Ostrea lurida*, in Tomales Bay, California, represents such an effort. Unfortunately, several impediments to the successful restoration of the oyster exist, most notably one of the "World's Worst Invasive Alien Species," the European green crab, *Carcinus maenas*.[1]

The European Green Crab

The European green crab, *Carcinus maenas*, has invaded both the East and West Coasts of the United States, establishing itself on the East Coast in the early 19th century and on the West Coast in San Francisco Bay in 1989.[2] In its native European range, from Norway to Mauritania, the green crab reduces the numbers of hard clams, *Mercenaria mercenaria* [3], blue mussels, *Mytilus edulis* [4], and Pacific oysters, *Crassostrea gigas*.[5] The

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[1] "One Hundred of the World's Worst Invasive Alien Species." IUCN, Invasive Species Specialist Group. Available online at http://www.invasives.org/. Accessed April 15, 2004.

[2] Cohen, A.N., J.T. Canton, and M.C. Fountain. 1995. Introduction, dispersal, and potential impacts of the green crab *Carcinus maenas* in San Francisco Bay, California. *Marine Biology* 122:225-238.

[3] Walne, P.R. and G. J. Dean. 1972. Experiments on predation by the shore crab, *Carcinus maenas* L., on Mytilus and Mercenaria. *Journal du Conseil International pour l'Exploration de la Mer* 34:190-199.

[4] Dare, P.J. and D.B. Edwards. 1976. Experiments on the survival, growth and yield of relaid seed mussels (*Mytilus edulis* L.) in the Menai Straits, North Wales. *Journal du Conseil International pour l'Exploration de la Mer* 37:16-28.

[5] Walne, P.R. and G. Davies. 1977. The effect of mesh covers on the survival and growth of *Crassostrea gigas* Thunberg grown on the sea bed. *Aquaculture* 11:313-321.

voracious appetite of the green crab has been blamed for the collapse of the soft-shell clam industry in Maine [6] and the decline of the scallop industry along the New England coast.[7] This global invader has also impacted shellfish in other geographic regions. In Tasmania, the green crab is believed to have affected the stepped verenid clam, *Katelysia scalarina*, fishery.[8] Its potential impact on shellfish beds along the West Coast appears inevitable, and it is believed *C. maenas* may already be impacting native commercial species such as the Dungeness crab, *Cancer magister*.[9]

The green crab can tolerate a wide range of salinity and temperature. Research indicates the green crab can survive in salinities ranging from 4 to 54 parts per thousand (ppt); average sea water has a salinity of 34-35 ppt. Green crabs can live in temperatures ranging from 0˚C to 33˚C. Additionally, an adult green crab can endure a starvation period of up to three months and air exposure of up to sixty days if sheltered by seaweed. Such a high level of resilience under a variety of stressors makes the green crab extremely capable of surviving long ocean voyages and reestablishing itself upon release.[10]

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[6] Glude, J.B. 1955. The effects of temperature and predators on the abundance of the soft-shell clam, *Mya arenaria*, in New England. *Transactions of the American Fisheries Society* 84:13-26.
[7] Fincham, M.W. An Endless Invasion? Green Crabs, New England Intruders, Move West. *Maryland Marine Notes Online* 14(2). Available online at http://www.mdsg.umd.edu/MarineNotes/Mar-Apr96/. Accessed 05 March, 2003.
[8] Walton, W.C., C. MacKinnon, L.F. Rodriguez, C. Proctor, and G.M. Ruiz. 2002. Effect of an invasive crab upon a marine fishery: green crab, *Carcinus maenas*, predation upon a venerid clam, *Katelysia scalarina*, in Tasmania (Australia). *Journal of Experimental Marine Biology and Ecology* 272:171-189.
[9] Gordon, D.G. and L. Mark. 2002. Armed and Dangerous: Who can stop this clam-killing crab? *Northwest Dive News*: Available online at http://www.wsg.washington.edu. Accessed 05 March, 2003.
[10] Yamada, S.B. 2001. *Global Invader: The European Green Crab.* Corvallis, OR:Oregon State University.

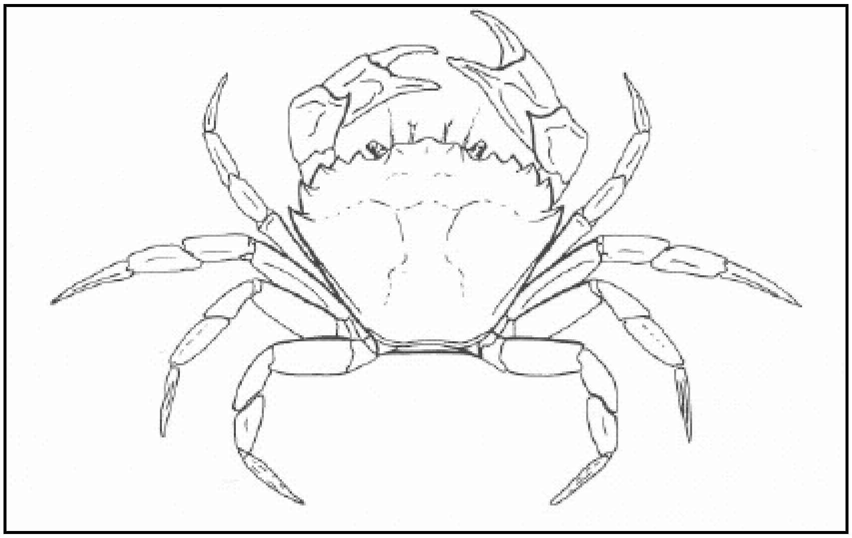

Figure 1. Drawing of the European green crab, *Carcinus maenas*. Source: Yamada, S.B. 2001. *Global Invader: The European Green Crab*. Corvallis, OR:Oregon State University.

The name "green crab" can be misleading, because green crab coloration varies from a mottled green to red, orange, and yellow. In their native range, adult green crabs can range from a 70 mm carapace in females to a 90 mm carapace in males, although recent studies show green crabs can grow even larger in their invaded habitats.[11] Green crabs can be distinguished from the native crabs in Tomales Bay by the five spines on their carapace - all native crabs in the Bay either have more or less than five spines (Fig. 1). For example, the *Hemigrapsus* (shore) crabs have three spines and the *Cancer* crabs have eleven.

An adult male green crab can be differentiated from an adult female by examining its abdomen. A male abdomen appears triangular, whereas a female abdomen appears as a rounded triangle (Fig. 2). Juvenile females often resemble males, and can be more difficult to sex. In order to sex crabs less than fifteen millimeters, one must pull back the abdomen and examine the pleopods. Males have two pairs of pleopods on abdominal

[11] Yamada, S.B. 2001.

segments one and two, whereas females have four pairs of pleopods on abdominal segments two through five.[12]

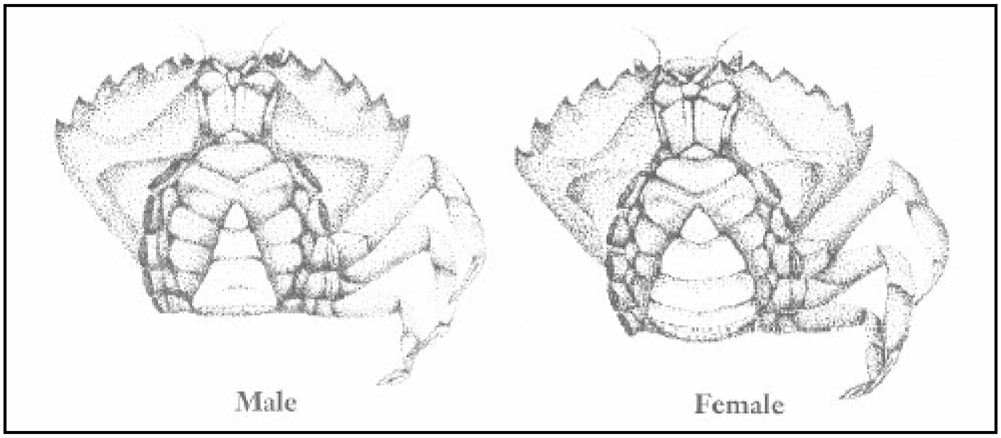

Figure 2. Abdomen of adult male and female *Carcinus maenas*. Source: Yamada, S.B. 2001. *Global Invader: The European Green Crab*. Corvallis, OR:Oregon State University.

Female crabs can produce up to 185,000 eggs per clutch.[13] Females brood their eggs for several months, and usually release them following a nighttime high tide.[14] Green crabs have six larval stages: one protozoea, four zoea, and one megalopa.[15] The larval stages can last from between thirty-two and sixty-two days, depending on water temperature. Green crabs have approximately seventeen crab stages. Females tend to become sexually mature by stages 12 or 13, and males by stage 9.[16]

In California, researchers first identified *C. maenas* in 1989-1990 in San Francisco Bay and Estero Americano. By 1993-1994, the crab had spread north to

[12] Yamada, S.B. 2001.
[13] Broekhuysen, G.J. 1936. On development, growth, and distribution of *Carcinus maenas* (L.). *Archives Neerlandaises de Zoologie* 2:257-339.
[14] Zeng, C. and E. Naylor. 1996. Synchronization of endogenous tidal vertical migration rhythms in laboratory-hatched larvae of the crab *Carcinus maenas*. *Journal of Experimental Marine Biology and Ecology* 198:269-89.
[15] Yamada, S.B. 2001.
[16] Ibid.

Bodega Harbor and south to Elkhorn Slough, a total coastal distance of 230 km (Fig. 3).[17] Scientists believe the green crab reached Tomales Bay in 1993.[18]

Although it is indefinite how the green crab reached San Francisco, eight different transport mechanisms are possible: ship boring and fouling assemblages, solid ballast, fouled seawater pipes and sea chests, semi-submersible exploratory drilling platforms, ballast water, seaweed transported with commercial fishing products, education/research, and private releases for fisheries purposes.[19] Researchers believe the green crab was introduced into the San Francisco Bay area via ballast water. In addition to the Pacific West Coast, the green crab has established populations throughout the world, including Australia, the Eastern United States, and South Africa (Fig. 4). The dates indicate the year green crabs were discovered at each location. The black lines indicate established populations of green crabs, whereas the grey lines show areas favorable to green crab settlement.

[17] Carlton, J.T., and A.N. Cohen. 2003. Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. *Journal of Biogeography* 30: 1809-1820.
[18] Grosholz, E.D. and G.M. Ruiz. 1995 Spread and potential impact of the recently introduced European green crab, *Carcinus maenas*, in central California. *Marine Biology* 122:239-247.
[19] Ibid.

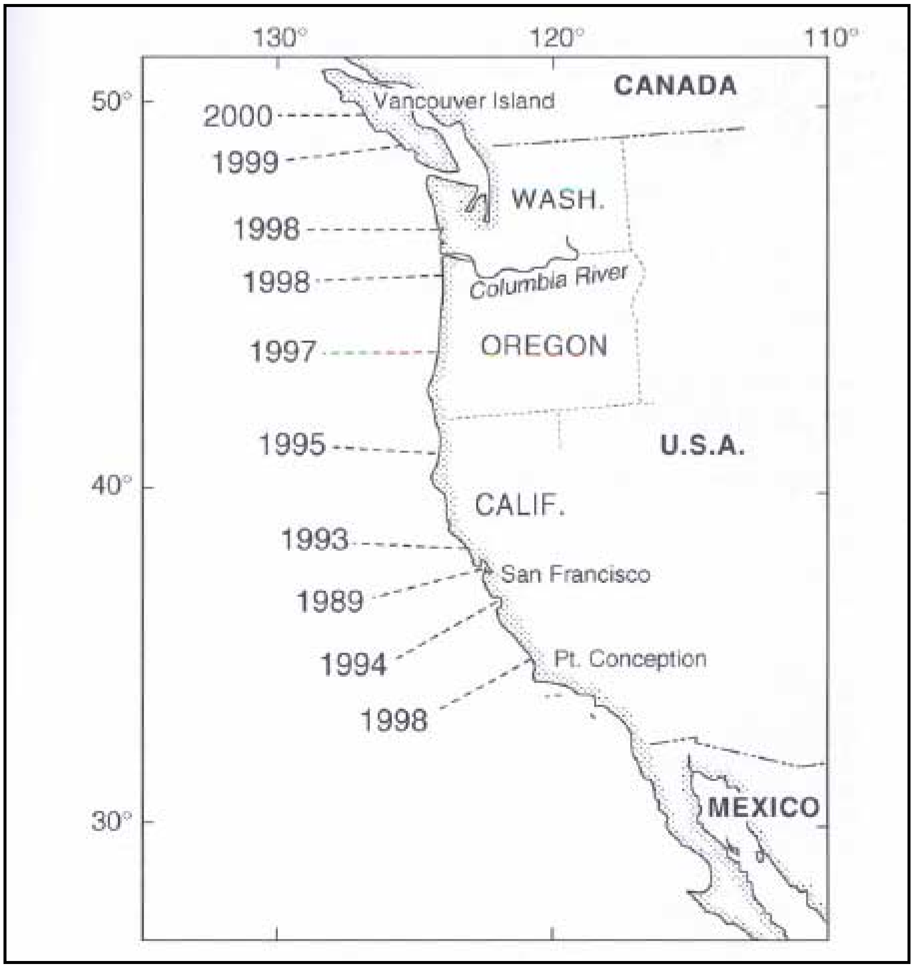

Figure 3. West Coast dispersion of *Carcinus maenas*. Source: Yamada, S.B. 2001. *Global Invader: The European Green Crab*. Corvallis, OR:Oregon State University.

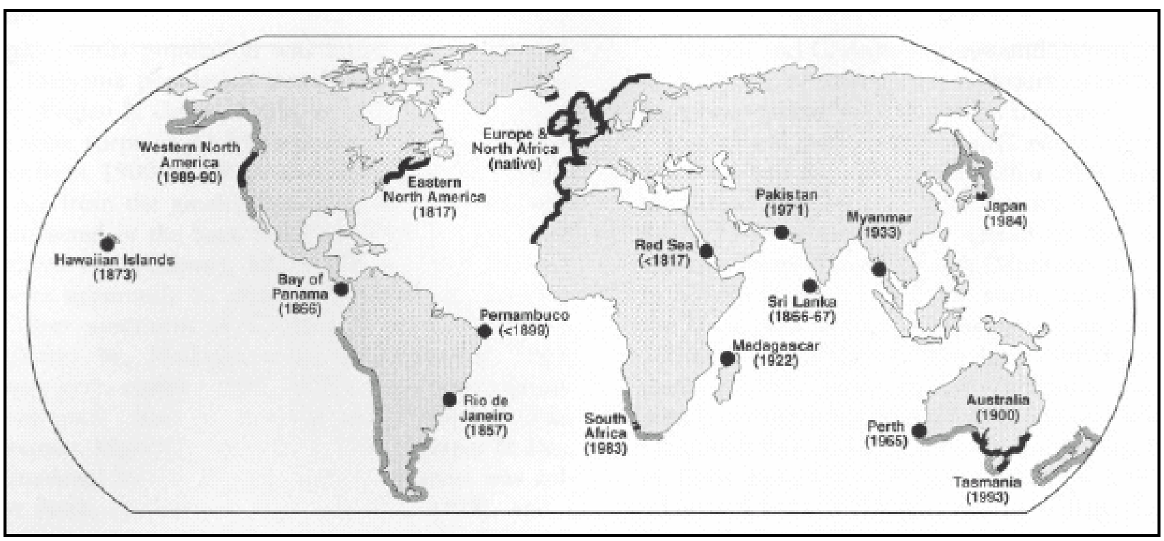

Figure 4. Global dispersion of the European green crab. Source: Carlton, J.T., and A.N. Cohen. 2003. Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. *Journal of Biogeography* 30:1809-1820.

The Olympia Oyster

The Olympia oyster, *Ostrea lurida*, ranges from Southeast Alaska to Baja California. The oysters served as an important food source for Native Americans – Indian kitchen middens found in the San Francisco Bay area reveal a significant number of Olympia oyster shells.[20] The population of oysters in Tomales Bay and the surrounding waters began to fall as Europeans settled the area and realized the food value of the oyster. In the 1850s and 60s people harvested the oyster in large amounts, and by 1870 overharvesting had significantly depleted the stocks.[21] Further declines in population numbers can be attributed to pollution, run-off from agriculture and mining, and erosion. Oyster harvesters attempted to increase the harvests by introducing the Pacific oyster, *Crassostrea gigas*. The inadvertent introductions of several species of oyster predators, including the Atlantic oyster drill, *Urosalpinx cinerea*, and a parasitic flatworm, *Mytilicola orientalis*, which were attached to the Pacific oysters, further contributed to the native oyster decline.[22] As early as 1979, some reduction in the oyster population number was thought to be caused by introduced species.[23] Today, no commercial harvesting of Olympia oysters takes place in California.

Olympia oysters are found at depths of zero to 71 meters.[24] The oysters are sensitive to extreme high and low temperatures, and can tolerate low salinities. Olympia

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[20] Couch, D. and T.J. Hassler. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--Olympia oyster. U.S. Fish Wildl. Serv. Biol. Rep. 82(11.124). U.S. Army Corps of Engineers, TR EL-82-4. 8pp.
[21] "Olympia oyster" Pacific Biodiversity Institute. Available online at http://www.pacificbio.org Accessed February 24, 2004
[22] Ibid.
[23] Carlton, J.T. 1979. History, biogeography and ecology of the introduced invertebrates of the Pacific Coast of North America. Ph.D. Thesis. University of California, Davis. 904 pp.
[24] Couch, D. and T.J. Hassler. 1989.

oysters can settle on substrate that is not "particularly clean."[25] The oysters grow slowly, reaching maturity at three years. Generally, most shell lengths average between 35 - 45 mm, and after three years most oysters do not experience much growth, if any (Fig. 5).[26]

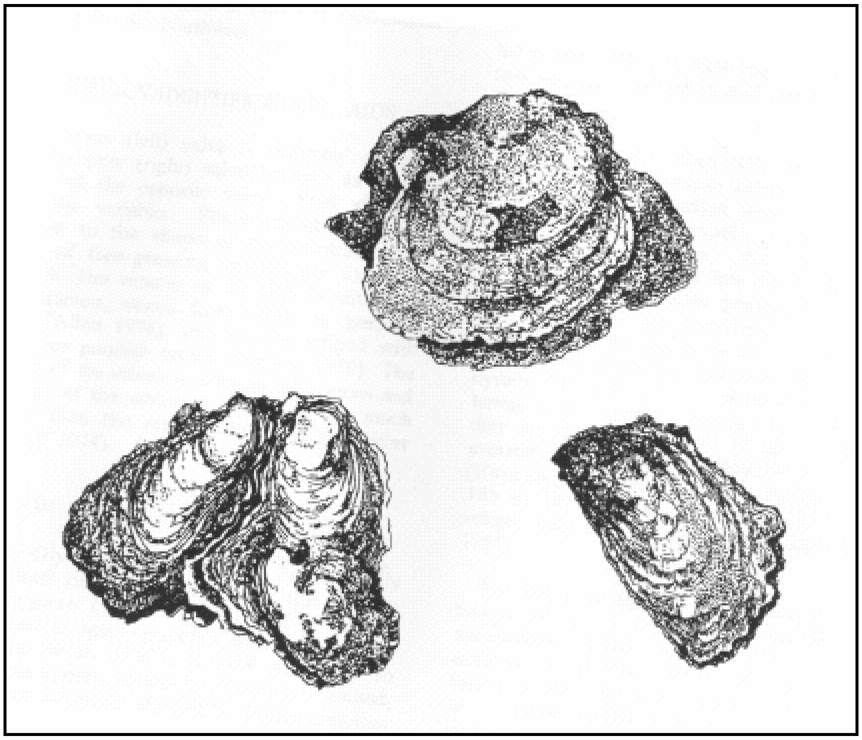

Figure 5. Olympia oyster, *Ostrea lurida*. Single, top; cultured, right; cluster, left. Source: Couch, D. and T.J. Hassler. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--Olympia oyster. U.S. Fish Wildl. Serv. Biol. Rep. 82(11.124). U.S. Army Corps of Engineers, TR EL-82-4.

Olympia oysters are filter feeders, relying on phytoplankton as a food source. Each individual oyster constantly filters water, taking in between 20-30 liters per hour, but polluted waters or pathogens can become concentrated in the oyster's tissues, leading to less efficient filtration, or death.[27]

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[25] Ibid.
[26] Ibid.
[27] "Olympia oysters" Pacific Biodiversity Institute. Available online at http://www.pacificbio.org Accessed February 24, 2004

In 1999, researchers from the University of California-Davis, the University of California Cooperative Extension, and the Sea Grant Extension Program began an Olympia oyster restoration project in Tomales Bay. Restoring the Olympia oyster into Tomales Bay offers several potential benefits. First, the oysters' constant filtering of the water may lead to water quality improvement in Tomales Bay. Tomales Bay is listed as an impaired body of water by the San Francisco Bay Regional Water Quality Control Board, and scientists believe the oyster can help improve the Bay environment. Second, the reefs provide increased habitat for other native fish and Bay species. According to scientist Mike McGowan, "More oysters would provide more habitat diversity as well as more species diversity."[28] Third, the oysters may eventually allow for the establishment of a small commercial fishery in Tomales Bay. Paul Olin, UCCE Sea Grant marine advisor, hopes that the oysters will "cling to shells [placed] on the bay bottom and continue to flourish in the bay."[29]

The researchers built artificial reefs out of pine two-by-fours and plastic mesh bags filled with old oyster shells (Fig. 6). Boats transported the reefs out into Tomales Bay. Orange buoys mark the placement of the reefs at high tide; at low tide the reefs are exposed.

[28] Oberthur, Anna. 2003. Scientists trying to restore native oysters, one of Tomales Bay's most important species. Associated Press. Available online at http://cw.groupstone.net. Accessed on February 2, 2004.

[29] Tognetti, Christine. 2002. UC research project working to restore native oysters in Tomales Bay. University of California, Division of Agriculture & Natural Resources. Available online at http://news.ucanr.org/. Accessed on February 2, 2004.

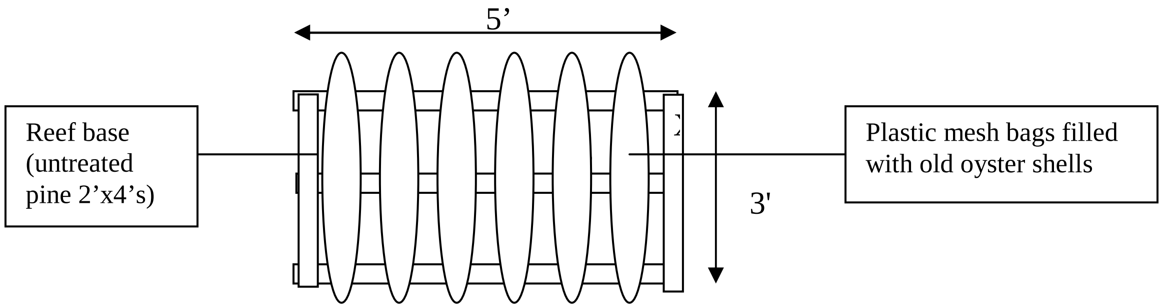

Figure 6. Oyster reef diagram.

Currently, reefs are in place at Tomasini Point and Tom's Point. Although both locations are on the East side of the Bay, Tom's Point is located near the mouth of the Bay, whereas Tomasini Point is in the middle. Researchers are trying to determine the best areas in the Bay for oyster recruitment and survival. Consequently, predation on the oysters, particularly by invasive species such as the oyster drill and the European green crab, is of interest to the researchers.

Tomales Bay

Tomales Bay is a thirteen-mile long bay situated approximately fifty kilometers north of San Francisco. The land surrounding Tomales Bay is both publicly and privately owned. Two protected areas, Point Reyes National Seashore and Tomales Bay State Park, surround parts of the Bay, while the remaining surrounding lands are coastal towns or cattle farms. The Tomales Bay watershed is comprised of 11,000 people and 22,000 cattle.[30]

[30] Smith, S.V. and J.T. Hollibaugh. "The Tomales Environment." Part of the Tomales LMER/BRIE Research Project. Available online at http://lmer.marsci.uga.edu/tomales Accessed on March 21, 2004.

Tomales Bay is part of the Gulf of the Farallones National Marine Sanctuary (GFNMS). President Jimmy Carter designated the Gulf of the Farallones National Marine Sanctuary in 1981. The Sanctuary encompasses an area of 1, 255 square miles and includes the offshore marine regions of the Farallon Islands and the nearshore waters of Tomales Bay, Bodega Bay, Estero de San Antonio, Estero Americano, and Bolinas Lagoon. GFNMS is adjacent to two other marine sanctuaries – Cordell Bank to the north and Monterey Bay to the south. Located in an area of high nutrient upwelling, the Sanctuary waters provide a rich environment for numerous animals, and support high levels of biodiversity, including thirty-three species of marine mammals, numerous species of commercially important fish, and the largest number of breeding seabirds in the continental United States.[31] Within the Sanctuary, Tomales Bay holds an important role in preserving the area's native coastal species, such as the Olympia oyster.

Objective

The objective of my study was to assess the impact of the invasive European green crab, *Carcinus maenas*, on the restoration of the native Olympia oyster, *Ostrea lurida,* in Tomales Bay, California. During July and August 2003, I worked at four field sites in Tomales Bay: Shell Beach, Tomasini Point, Tom's Point, and Nick's Cove (Fig. 7). Two of these sites, Tomasini Point and Tom's Point, are established reef areas, and two of the sites, Shell Beach and Nick's Cove, are potential reef areas. Shell Beach and Nick's Cove are rocky intertidal habitats. Tomasini Point and Tom's Point are mud flats.

[31] "Gulf of the Farallones Natural Setting," National Ocean Service/NOAA. Available online at: http://www.sanctuaries.nos.noaa.gov/oms/omsfarallones/omsfaralnatset.html. Accessed December 5, 2003.

Figure 7. Map of Tomales Bay and four field sites.

Methods

Trapping Protocol for Crap Abundance Estimates and Reef Trap-Outs

I took green crab population estimates at three sites: Shell Beach, Nick's Cove, and Tomasini Point. I conducted trap-out experiments at two sites: Tomasini Point and

Tom's Point. Tom's Point had one set of reefs; Tomasini Point had two sets of reefs (A and B). At the time of the population estimate trapping, the reefs at Tomasini Point had not yet been deployed. I assisted in deploying the reefs, and two weeks later, I returned to Tomasini Point to determine if green crabs had colonized the reef areas, and in what numbers. The reefs at Tom's Point had been in place for one year.

At each site, fish traps (0.5 x 0.5 x 0.2m) were set at varying tidal heights, with at least 10 meters between traps. Minnow traps that were more likely to catch small crabs were deployed between the fish traps. I based this method on past green crab trapping protocol.[32] Based on UC Davis researcher suggestions, eight traps - four minnow and four fish - were placed at the following sites: Shell Beach, Site A and B; Nick's Cove, Site A and B; and Tomasini Point, Site A and B.

When trapping out at the reefs, I placed the traps around the reefs. When trapping out along the reefs at Tomasini Point, each individual reef area had one fish trap and one minnow trap, or two fish traps, depending on the size of the reef. At Tom's Point, two fish traps and four minnow traps were used. The reefs in Tomasini Point had been in place for two weeks, whereas the Tom's Point reef had existed for one year. Olympia oyster recruitment at the Tom's Point reef was low for 2002-2003, but oyster recruitment in the Tomasini Point area was high in 2003, according to a local oysterman.[33]

When taking population estimates, I re-released the crabs at the site after recording their information. At the reef trap-out sites, I removed the crabs from the area and either destroyed them or released them several miles away into Tomales Bay. For all trapped crabs, I identified species, sex, reproductive status, missing legs, and

[32] Grosholz, E. and C. diRivera. June 2003. Personal communication.
[33] Grosholz, E. July 2004. Personal communication.

measured carapace size. I released native crabs and other species, such as fish, at the site.

Following the data collection, I organized the data according to reef site and date. I calculated green crab abundance estimates by totaling all of the trapped green crabs for each site. To analyze the trap-out data, I used a simple correlation to determine the strength of relationship between days trapping out and the number of crabs trapped each day.

Protocol for Laboratory Feeding Experiments

I filled four two hundred liter outdoor tanks with sea water. In each tank, I placed one cobble with Olympia oysters. The number of oysters varied per cobble. I placed one green crab in each tank. I measured carapace width of each crab and noted sex. Carapace width varied from 36 mm to 57 mm. Six males and two females were used in the experiment. [Note: I favored male crabs in this experiment because their claws tend to be stronger and their appetites more voracious than females]. To standardize hunger levels, I starved the crabs for twenty-four hours prior to placing them in the tanks. The crabs stayed in the tanks for five days, and I examined the cobbles every twenty-four hours to observe what (if any) oysters were eaten. After five days, the crabs were removed from the tanks and destroyed. I measured the length and width of each consumed oyster's shell with a standard caliper. In several cases, the remaining oyster shell was only a partial remnant, preventing me from measuring both length and width.

To analyze the feeding experiment data, I divided the oysters into four size classes, and the crabs into three size classes. I put the consumed oysters into four size classes based on shell length: 3.5-12.9 mm, 12.5-21.9 mm, 21.5-30 mm, and greater than 30 mm. I divided up the green crabs into three size classes: small, medium, and large. Small crabs measured between 30 and 39 mm, medium crabs measured between 40 and 49 mm, and large crabs measured between 50 and 59 mm. I calculated the percentage of available oysters in each size class consumed by the crabs in each size class.

Results

I trapped a total of 750 European green crabs. I found the highest number of green crabs at the two rocky sites: Shell Beach traps resulted in 235 crabs and Nick's Cove resulted in 215 crabs. Tom's Point had a total of 48 crabs. Prior to reef deployment, I trapped 94 crabs at Tomasini Point, but two weeks after reef establishment, I caught 158 green crabs. From these numbers, I observed a higher number of green crabs in rocky areas than in mud flat areas. Also, I saw an increase in the number of green crabs at Tomasini Point from the initial trapping to the post-reef deployment trapping.

The trap-out results from Tom's Point and Tomasini Point are graphed. Tom's Point and Tomasini Point, Reef A, show an overall decrease in number of green crabs over the five day trapping period (Figures 8 and 9). Tomasini Point, Reef B, shows a sharp increase between the first and second day, and a decrease from the second to third day (Figure 10). This reef area was plagued by traps being removed from the site by an unknown organism during the first twenty-four hours of trapping, which may have affected the number of crabs I caught.

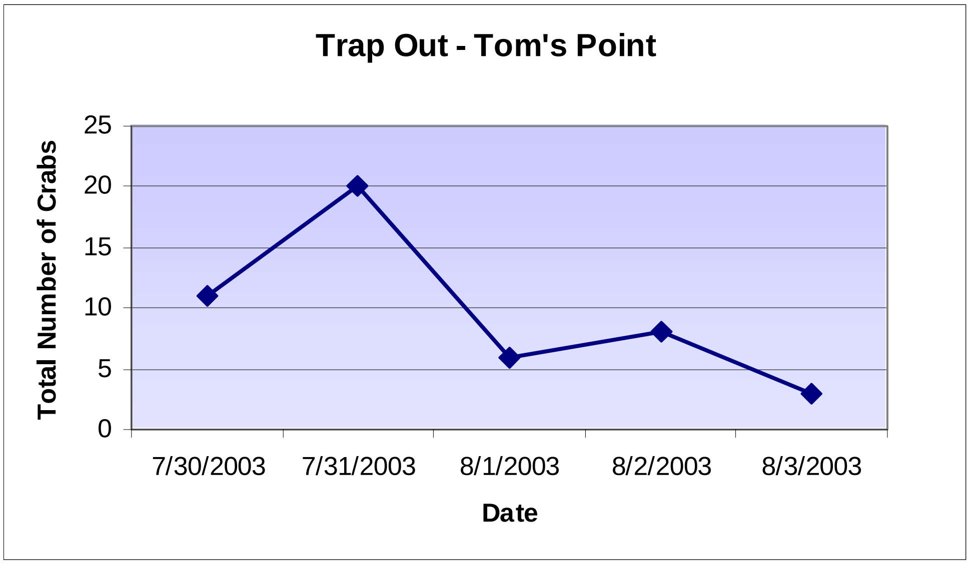

Figure 8. Trap-out results from Tom's Point

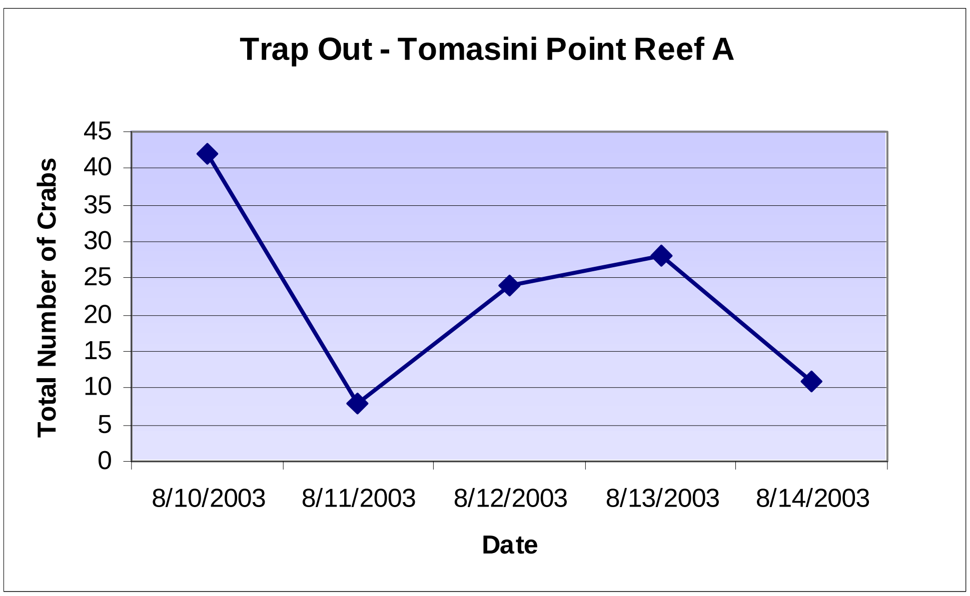

Figure 9. Trap-out results from Tomasini Point, Reef A

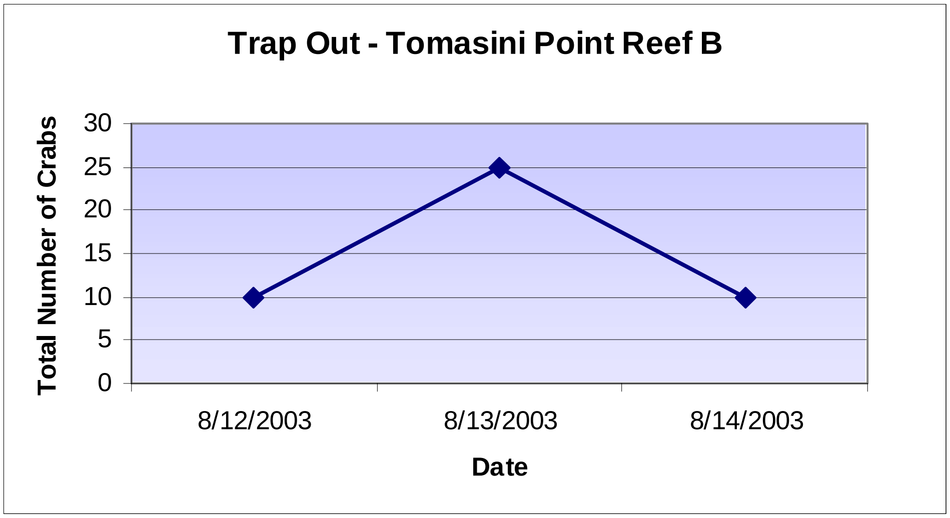

Figure 10. Trap-out results from Tomasini Point, Reef B

The correlation between the total number of green crabs against the date at Tom's Cove is -0.680703294. The correlation between the total number of green crabs against the date at Tomasini Point Reef A is -0.483301674. Both of these correlations suggest that the number of green crabs becomes smaller over time, and possibly results from removal of the crabs by way of trapping. The correlation between the total number of green crabs against the date at Tomasini Point Reef B is zero. This may be due to the fact that several of the traps did not catch crabs on the first day because they were removed from the trapping site by an unknown force. (I found one fish trap and two minnow traps scattered about the site, with the bait removed from the fish trap.)

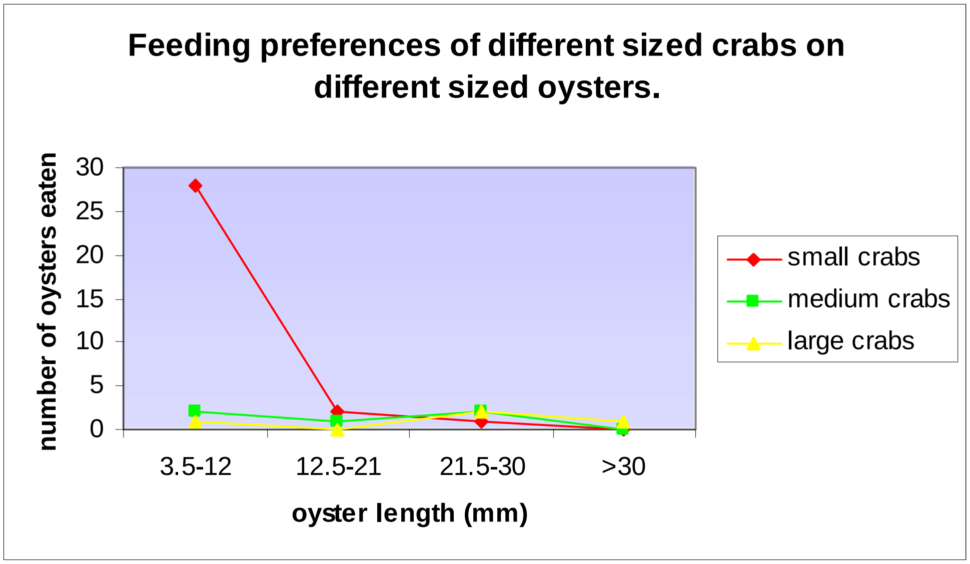

Figure 11. Feeding preferences of different sized crabs on different sized oysters.

Crab Size Class (mm)

Oyster Size Class (mm)

	30-39	**40-49**	**50-59**
3.5-12.49	58%	5%	3%
12.5-21.49	10%	4%	0
21.5-30.49	6%	13%	15%
>30	0	0	14%

Figure 12. Percentage of available oysters consumed by each crab class.

The feeding experiments indicate that the number of oysters consumed decreased as oyster size increased (Figure 11). Figure 12 shows the percentage of available oysters consumed by each size class of crab. The small class of crabs (30-39mm) consumed 58% of the small oysters available to them. The small crabs consumed the greatest number of oysters, 31 in total, and the greatest number of the smallest size class of oysters, 28. The medium crab class consumed a total of five oysters over the feeding period, two in both the smallest and second largest class, and one in the second smallest class. The large crab class consumed four oysters over the feeding period, with only one in the small size class, two in the second largest size class and one in the largest size class. With the exception of one large oyster being consumed by the largest crab classes, the two other crab classes did not prey upon the largest oyster class.

Discussion and Conclusions

My population estimates indicate that green crabs are more abundant in rocky areas than in mud flat areas. This makes sense, as rocks provide shelter for green crabs and their prey. When developing areas for oyster reef deployment in the future, researchers may want to consider areas similar to Tom's Point and Tomasini Point, and avoid rocky areas. Such areas are useful for establishing reefs, but over time the reefs become hard substrate and attract crabs and other predators.

Although my results indicate that trapping-out offers a possible short-term solution to controlling crab numbers, the green crab is well-established in Tomales Bay, and due to the planktonic larvae and mobile adults, which can swim up to 15 km, the green crabs will most likely recolonize the reefs.[34] Therefore, trapping out would have to be done on a continuous basis with the crabs removed from the area and destroyed. This is time consuming, but may assist the Olympia oysters in becoming established.

From the feeding experiments experiments, I know that the green crabs do prey upon the Olympia oyster. The predation levels may have been influenced by the fact that

[34] Gomes, V. 1991. First results of tagging experiments on crab *Carcinus maenas* (L.) in the Ria de Aveiro Lagoon, Portugal. *Ciência Biológica Ecology and Systematics* (Portugal) 11(1/2): 21-29.

the tanks of the green crabs were not covered, thus increasing the water temperature and impacting their appetite. The high percentage of small oysters consumed is important because crab predation on such small oysters may prevent the oysters from reaching a harvestable size.

This theory is supported by past research. A 2003 study indicates that blue mussel dominance in the western Baltic Sea is mainly controlled by the green crab.[35] The researchers discovered the green crabs consumed mussels of various size classes. The small crabs (3.0-4.9 cm) preferred the smallest mussels (0.5-1.4cm), the medium crabs (5.0-6.4 cm) preferred the second smallest mussels (1.5-2.4 cm), and the large crabs (6.5-8.0 cm) preferred the second largest mussel class (2.5-3.4 cm), but consumed the greatest amount of mussels from the largest mussel class (3.5-4.4 cm).[36] Other studies indicate green crabs have the potential to prevent other shellfish species, such as clams, from reaching a harvestable size.[37]

The Olympia oyster restoration project faces additional obstacles. Other invasive species may influence the success of the oyster, specifically the presence of the invasive oyster drill, *Urosalpinx* sp. Ongoing research is looking at the impact of these drills on the oysters. Pollution into Tomales Bay continues to be a problem, occasionally shutting down the Bay's existing oyster farms. The area of the bay where the reefs are located may also contribute to the success of the restoration project. If certain areas experience rough waters, oyster settlement may be lower there than in calmer areas. Also, the tidal

[35] Enderlein, P., S. Moorthi, et. al. 2003. Optimal foraging versus shared doom effects: interactive influence of mussel size and epibiosis on predator preference. *Journal of Experimental Marine Biology and Ecology*. 292:231-242.
[36] Ibid.
[37] Jensen, K. and J. Jensen. 1985. The importance of some epibenthic predators on the density of juvenile benthic macrofauna in the Danish Wadden Sea. *Journal of Experimental Marine Biology and Ecology* 89: 157-174.

exchange of one area of the bay may provide more favorable conditions for oyster settlement. Finally, annual fluctuations in both the crab and oyster populations may influence the oyster recruitment and survival rates.

A nine-year study focusing on Bodega Bay Harbor, located directly north of Tomales Bay, showed a ten-fold decrease in the native shore crab, *Hemigrapsus oregonensis*, within three years of the green crab introduction into the Bay.[38] Also, two native clam species, *Nutricola tantilla* and *Nutricola confuse,* showed declines of five times their mean density following the green crab introduction.[39] Green crabs may use the oyster reefs as shelter, thus increasing the possibility of predation. Mussel beds and shell piles serve as a refuge for juvenile green crabs on tidal flats in the Wadden Sea.[40] Additional research shows that *C. maenas* competes for refuge habitat with the native Dungeness crabs, *Cancer magister*, of the Pacific coast.[41] Obviously the green crab poses a serious threat to native species, especially those with which it competes for food and shelter and those it consumes. Management of the green crab around the Olympia oyster reefs is vital to the success of the restoration project.

Alternatives to trapping out exist, and include mesh coverings, fences, and biological control agents. Previous research shows that green crab predation on oysters can be reduced significantly by protecting the oysters with a mesh covering.[42] Walne & Davies showed that a 12.5-mm mesh cover provided a "substantial degree of protection"

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[38] Grosholz, E.D., G.M. Ruiz, et al. 2000. The impacts of a nonindigenous marine predatory in a California Bay. *Ecology* 81(5):1206-1224.
[39] Ibid.
[40] Thiel, M. and T. Dernedde. 1994. Recruitment of shore crabs *Carcinus maenas* on tidal flats: mussel clumps as an important refuge for juveniles. *Helgol. Wiss. Meeresunters*. 48(2-3):321-332.
[41] McDonald, P.S., G.C. Jensen, and D.A. Armstrong. 2000. The competitive and predatory impacts of the nonindigenous crab *Carcinus maenas* (L.) on early benthic phase Dungeness crab *Cancer magister* Dana. *Journal of Experimental Marine Biology and Ecology* 258:39-54.
[42] Walne, P.R. and G. Davies. 1977.

to the Pacific oyster, *Crassostrea gigas*, and theorized that the "use of a relatively simple cover can lead to a marked increase in the survival of small oysters and … in growth."[43] As Olympia oysters tend to be smaller and grow at slower rates than the Pacific oyster, such mesh coverings may prove useful in protecting the oysters from green crab predation.

A second alternative to trapping out is the use of fences around the reef areas. Smith showed that 36 cm-high fencing of 2.5 cm chicken wire surrounding clam beds served to protect the clams from green crab predation.[44] Fencing has several drawbacks; however, and I do not recommend it be used to mitigate green crab predation on the Olympia oysters. Fencing can be expensive to construct and would require regular maintenance. Of greater impact to the restoration project, though, is the fact that the fences would preclude the development of the reef area into habitat for native species. One of the three goals of the oyster restoration project is to provide habitat for native Bay species, and the use of fences would prevent the achievement of this goal.

A third alternative is the introduction of a biological control agent. Although biological control agents offer a potential means of green crab control, they are extremely controversial. In the past, biological control agents, introduced to control invasive species, have attacked native species instead, often decimating their populations. For example, managers introduced the rosy wolfsnail, *Euglandina rosea*, into Hawaii in 1955 in the hopes that it would prey upon the invasive giant African snail, *Achatina fulica*, an agricultural pest and general nuisance species. Instead of eating the African snail, the rosy wolfsnail attacked non-target native species and is blamed for the extinctions of

[43] Ibid.
[44] Smith, O.S. 1950. Fencing in flats may save some clams from green crabs. *Maine Coast Fisherman* 8(8):20.

between fifteen and twenty species of native Hawaiian snail.[45] Similar examples involving terrestrial and marine species abound, and are reasons to avoid the use of biological control agents.

Currently, several potential biological control agents exist for green crabs, including parasitic egg castrators and egg predators. The parasitic barnacle, *Sacculina carcini*, affects green crabs in their native range, and has been tested in the laboratory as a way to control the crabs in their invaded environments. Researchers studying the impact of *S. carcini* on four native crabs of the Pacific coast, including the Dungeness crab, *Cancer magister*, found that the barnacle infested all native crabs.[46] Additionally, all infected native crab species died within 154 days of infection; infected green crabs lived up to 355 days with the infection.[47] Although additional studies need to be done on other biological control agents, I do not recommend the introduction of a biological control agent into Tomales Bay at this time; the potential repercussions to native species are too great.

Although several alternatives to trapping out exist, the only one I recommend for consideration is the use of mesh coverings around the reefs. The others pose too great a risk to either the goals of the project or the survival of native Bay species. Perhaps future studies will reveal additional control methods for the green crab.

Unfortunately, restrictions such as tidal schedules, available traps, and lack of resources prohibited me from additional trapping. To develop more concrete

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[45] Civeyrel, L. and D. Simberloff. 1996. A tale of two snails: is the cure worse than the disease? Biodiversity and Conservation 5:1231–1252.
[46] Goddard, J.H.R., M.E. Torchin, K.D. Lafferty, and A.M. Kuris, 2001. Experimental Infection of Native California Crabs by *Sacculina carcini*, a Potential Biocontrol Agent of Introduced European Green Crabs, University of California. Proceedings of the Second International Conference on Marine Bioinvasions, New Orleans, La., April 9-11, 2001, pp. 54-55.
[47] Ibid.

conclusions, further trapping will need to be done, as well as additional replicates of laboratory feeding experiments. I suggest trapping out around the reefs for an extended period of time to get a better idea of green crab recolonization rates, and whether continued trapping will make a difference in the number of green crabs around the reefs. My results indicate lower numbers of green crabs at mud flats than in rocky areas; trapping in more mud flat and rocky areas to get added population estimates can further support this.

I advocate replicating my feeding experiments to get a larger sample size of green crabs and oysters. I am interested in whether there is an oyster size at which the green crabs expend more energy attempting to open the oyster, and therefore do not consume the oyster. If native oysters could be grown in a protected environment until they reached a certain size, would green crab predation around the reefs be reduced?

Many factors will influence the Olympia oyster restoration project in Tomales Bay. The high population of green crabs in Tomales Bay and the surrounding waters make total eradication impossible. However, the potential exists to control the green crab population around the reef areas. If green crab predation on the oysters can be minimized through trapping or low-risk alternatives, the oyster restoration project has a great chance of success. Not only will the project's success mark an achievement for native biodiversity protection in the Bay, it will also preserve a unique cultural resource of Tomales Bay, the Olympia oyster fishery.

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