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GREEN CRAB MANAGEMENT: REDUCTION OF AN INVASIVE POPULATION

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INTRODUCTION

While most invasive species policy and management efforts focus on prevention or reducing the risk of new invasions, introductions are inevitable due to the many vectors that cannot be regulated without impacting trade. In addition, many established marine nonindigenous species (NIS) already impact ecological communities, commercial fisheries, or physical habitat structure (Carlton 2001, Grosholz 2002). Therefore, recently managers and scientists who recognize the need for additional tools for controlling introduced species have become interested in eradication as a management tool.

Many eradication efforts have succeeded, especially in New Zealand, where 92.7% of 153 attempts were successful (Courchamp et al 2003). Mammal eradications are most common (~ 500 successes), but managers have eliminated other introduced taxa from islands as well (Krajick 2005). Removal is now occurring on ever-larger islands (e.g., Genovesi 2005), archipelagos (e.g., Simberloff 2002) and even mainland areas. For example, the Canadian beaver was eliminated from France (Lorvelec & Pascal 2005) and an *Anopheles* mosquito was eliminated from Brazil (Davis & Garcia 1989). While the most effective time to eradicate an introduced species is when it first arrives, this does not mean that established, widespread populations cannot be eradicated (Simberloff 2003).

Considerably fewer eradication attempts have been tried in marine systems (Carlton 2001) due to outdated perceptions of marine habitats. The idea of high connectivity and unlimited dispersal in the ocean has reduced the sense of the effectiveness of local management. However, evidence is mounting that local control and eradication initiatives have local results, even in marine systems (Thresher & Kuris 2004). Furthermore, even continuous systems lack high connectivity (Cowen et al 2006). Similarly, Byers & Pringle (2006) show that bays have high larval retention and, like habitat islands, present at least a partial barrier to recruitment into or dispersal from the area. Such localized recruitment was predicted to explain why green crabs have such slow range expansion in Australia, South Africa, and eastern North America (Thresher et al. 2003) and may explain similar trends in other marine invaders (Grosholz 1996).

Lower connectivity suggests marine eradications are indeed feasible. Recent examples of successful eradication of marine NIS are increasing and include elimination by poisoning (e.g., Anderson 2005) as well as physical removal (Culver & Kuris 2000, Miller et al 2004, Thresher & Kuris 2004). A broad-based workshop endorsed physical removal over other management options because it is less likely to cause irreversible unintended damage (Thresher & Kuris 2004). Therefore, it is important to identify whether physical removal can be effective in marine habitats at all scales and for established populations.

The overall goal of this study is to develop and demonstrate the capacity for local eradication of adult *Carcinus maenas*, European green crabs. This represents a conceptual shift in development of management options to address established invasions in marine systems, extending and exploring the application of terrestrial successes in this area. Specifically, this project tests the effects of removing green crabs from Bodega Harbor on the green crab population and on native shore crabs eaten by green crabs.

METHODS

After sampling green crab densities across Bodega Harbor to obtain relative abundance estimates per habitat, we focused most of our removal efforts in the lower intertidal zone of the five highest-abundance sites to maximize returns. We also periodically trapped throughout the bay and trapped and trawled the deeper main channel of Bodega Harbor to increase our trapping coverage and to determine whether green crabs use deeper areas, especially during the winter. The standard trapping protocol included deployment of 10 baited traps, five standard minnow traps and five collapsible fish traps, evenly spaced along a 225 m transect parallel to the water at each site for 24 hr ± 2 hr periods. Except for our mark-recapture and census periods used for comparison with other bays (see below), we removed all green crabs trapped from Bodega Harbor since July 13, 2006.

We used mark-recapture (MR) sampling to estimate the initial local population size of adult *Carcinus* and to provide a baseline estimate to use to track the decline in the Bodega population. Enough marked and captured crabs at three sites were obtained for subpopulation estimates. We marked crabs using coded microwire tags.

We followed a before-after-control-impact (BACI) study design to identify changes in abundance independent of our management efforts. To obtain abundance estimates of surrounding populations, we compared green crab catch per unit effort at four sites in Bodega Harbor with nearby bays before and three times after the start of removal.

To identify whether control of green crabs benefits native organisms, we tracked the abundance and survivorship of native shore crabs, *Hemigrapsus oregonensis* at all *Carcinus* sampling sites. We also conducted a tethering study to examine how relative predation pressure on shore crabs changed with green crab removal. We tethered 10 crabs at each of six sites in Bodega, ranging from areas with low to high *Carcinus* abundance.

RESULTS

Our initial round of sampling identified an uneven distribution of crabs throughout the bay and throughout the intertidal zone, with sites varying from 0 to 17.8 *Carcinus* per trap. The tidal zone at which traps were deployed affected the catch (ANOVA: $F_{2,9}$ = 3.56, P = 0.0724), with more crabs caught in shallow subtidal (47.41+/- 17.64, mean +/-

SE, n = 4) than mid tidal areas (8.00 +/- 3.00). Traps set just above the daily lower low tide mark had an intermediate catch (21.1 +/- 4.34). Therefore, we focused most of our removal efforts on the lower intertidal zone to submerged areas. The minnow traps caught smaller crabs and more females than did larger traps. Neither the trapping nor the trawling of the channel yielded any *Carcinus*.

At the highest abundance site, the Schnabel mark-recapture method estimated 3,141 adult *Carcinus* and the Petersen method estimated 2,925. Around 2000 crabs were estimated at the next-most abundant sites (Dorm Channel Schnabel: 1,982 Petersen: 1,947 *Carcinus*; Owl Canyon Schnabel: 1,965 Petersen: 1,792. We recaptured 67% of the 2106 marked green crabs within three months.

In the 66 trapping days from 7/15/06-12/31/06, we removed 9,691 green crabs from Bodega Harbor, an average of 147 crabs caught per trapping day. Green crab numbers declined continuously in the Harbor across this period (Fig. 1). Before removal, the catch per unit effort (CPUE) of green crabs averaged 21.3 crabs per trap (N=10 days, with 10-19 traps). In contrast, CPUE for our ten trapping days in November plus December was quite low --1/15th the original catches--, averaging 1.4 green crabs per trap.

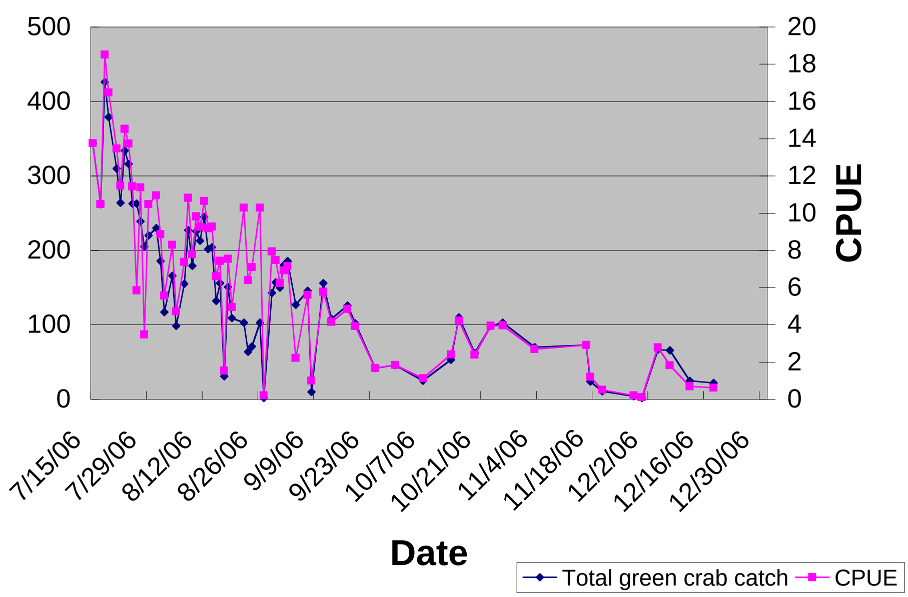

Figure 1. Green crab catch (total catch and CPUE) in Bodega Harbor, CA, 7/15 – 12/ 31/06.

Corresponding to the decreased catch was a decrease in green crab size from the start of removal through the end of August (Kolmogorov-Smirnov D = 0.35, P < 0.001). The sizes have since increased, probably due to individual growth. The initial decrease in size reveals substantial removal of large crabs that at times prevented smaller ones from entering traps (observed). In addition, the percentage of trapped female green crabs increased over time. Females initially may have been excluded from traps by aggressive males, else their behavior varies seasonally.

Catches also declined in the unmanipulated Tomales Bay and Elkhorn Slough, despite no crab removal from these bays. This trend suggests that crabs are less active or are using deeper water during our most recent cross bay comparison (January, 2007). Because the low catches in Bodega Harbor started before cold temperatures (Fig. 1) and we did not catch green crabs in our winter traps and trawls of the channel, we expect the low catches of Bodega Harbor will continue even as the water warms. Therefore, continued removal of the remaining green crabs from Bodega Bay and warm weather comparisons with control bays are expected to reveal more substantial differences between our target bay and other bays. In contrast to Bodega Harbor, carapace width did not decrease in these other bays in the same timeframe. The size distribution of crabs from Tomales was consistent across seasons, while the sizes of crabs in Elkhorn Slough increased significantly (Kolmogorov-Smirnov D = 0.244, $P < 0.001$).

We have not yet found significant increases in the number of native shore crabs, *Hemigrapsus oregonensis*, in our traps despite the decreases in green crab numbers. However, the survivorship of tethered shore crabs changed significantly across sites and with green crab removal (Fig. 2). Fewer tethered *H. oregonensis* were consumed in sites where many green crabs were removed. Initially we found that survivorship of tethered *H. oregonensis* decreased with increasing green crab abundance. After green crab abundances decreased, this relationship was no longer strong.

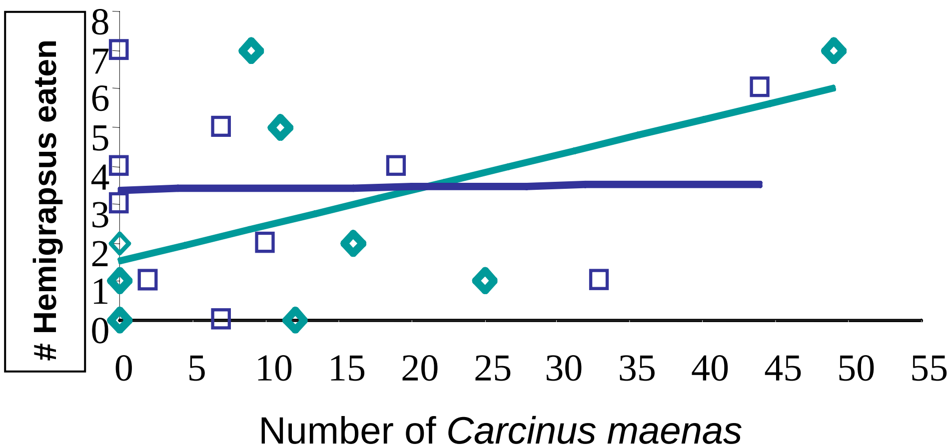

Figure 2. Number of tethered native shore crabs,* Hemigrapsus oregonensis, *consumed at each site versus the abundance of green crabs, Carcinus maenas, at the site for July (diamonds: $r^2 = 0.26$) and August (squares: $r^2 < 0.01$) 2006.

MANAGEMENT IMPLICATIONS

It is premature to judge whether this established population of a wide-ranging crab species can be brought down to zero or how long no to low crab numbers will persist. However, green crabs are now at low enough numbers, within a year of the start of control efforts, that trapping effort can be greatly reduced. Moreover, the removal of these invasive predators seems to be improving the survivorship of native shore crabs that had been affected by *Carcinus*. Our sampling in Bodega will continue at least through autumn 2008 to determine the longer term impacts to green crab demographics and native biota recovery.

Smaller-scale multi-year efforts likely could reduce green crab populations if they focus removal efforts on the lower intertidal areas of high density sites in warm weather. However, removal should persist well beyond decreased catches of large males to ensure that females and juvenile crabs are also removed.

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