Effects of ghost fishing on the population of red king crab (*Paralithodes camtschaticus*) in Womens Bay, Kodiak Island, Alaska

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Abstract—Ghost fishing, the capture and killing of marine organisms by lost or abandoned fishing gear, is a serious ecological and economic problem confronting fisheries. In this study, we quantify the rate of ghost fishing on the population of red king crab (*Paralithodes camtschaticus*) in Womens Bay, Kodiak Island, Alaska. From 1991 to 2008, crabs with carapace lengths (CLs) from 42 to 162 mm were tagged with acoustic tags and tracked both from a boat at the surface and by divers. Diver observations were used to determine whether a crab molted or died and, in many cases, to determine the cause of death. Of 192 crabs tracked during this study in association with other projects, 13 were killed in ghostfishing gear (12 in ghost crab pots and 1 in a ghost gill net) and 20 were captured in ghost pots and released alive by divers. An additional 13 died of other causes, including predation by sea otters and an octopus and poaching by humans. We estimate that between 16% and 37% of the population of red king crab with CLs >60 mm in Womens Bay were killed by ghost fishing per year during the period of this study, making ghost fishing a substantial source of mortality. These results indicate that steps to reduce ghost fishing in Womens Bay are warranted.

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Ghost fishing is the capturing and killing of marine organisms by fishing gear that has been lost or abandoned (Smolowitz, 1978) and is a serious economic and ecological problem in fisheries around the world (Breen, 1990; Laist, 1996; Matsuoka et al., 2005). Even after they are lost, nets can continue to entangle and kill organisms (Kaiser et al., 1996; Santos et al., 2003; Baeta et al., 2009), and fish traps and crustacean pots can continue to attract, trap, and kill target and nontarget species (Stevens et al., 2000; Hebert et al., 2001; Erzini et al., 2008; Ramirez-Rodriguez and Arreguin-Sanchez, 2008), such as reptiles, birds, and mammals (Havens et al., 2008; Good et al., 2009; 2010). Dead animals in crab pots and fish nets can then act as bait to attract even more organisms (Havens et al., 2008). Although in some cases these effects are negligible, in many cases, depending on the type of gear and the environment (Gerrodette et al., 1990; Santos et al., 2003), ghost fishing represents a substantial economic loss to the fishery (e.g., Breen, 1987).

One of the major difficulties in the estimation of the effects of ghost fishing is the methods that are typically used. Many studies either recover lost gear and determine the number of organisms caught (e.g., Stevens et al., 2000) or deliberately "lose" and follow the gear over time (Bullimore et al., 2001). In both cases, however, extrapolation of the results to the population level with any certainty is difficult because of the many important factors that must be estimated on the basis of limited information, including the rate of gear loss, rate of gear decay, and population size of the study organism. In addition, animals that escape may suffer delayed mortality in response to starvation during the captivity period (Paul et al., 1994), and this effect often is unaccounted for (e.g., Breen, 1987).

In this study, we took the unique approach of tracking individuals in a population of red king crab (*Paralithodes camtschaticus*) over time and observed their fates by tagging them with acoustic tags and by making in situ observations during scuba diving. This work allowed us to calculate the mortality rate caused by ghost fishing at the population level independent of population size (e.g., Lambert et al., 2006) and to compare it directly with other causes of mortality, such as predation. In addition, rather than focusing on one particular type of gear, this approach included all types of ghostfishing gear that were catching red king crabs in the study area and allowed comparisons among these gear.

This study took place in Womens Bay, which is located in the Gulf of Alaska near the city of Kodiak on Kodiak Island, Alaska, and is a popular site for commercial, sport, and subsistence fishing for a variety of finfish and shellfish species (Fig. 1). Red king crab was the major fishery species in the Gulf of Alaska during the 1960s, but populations of this crab crashed in the 1970s and 80s. The commercial fishery was closed in 1983 and has not been reopened (Orensanz et al., 1998). Since that time, red king crab has been harvested in this region only in a subsistence fishery for which the catch limit has been 3 crabs per household per year. In this fishery, only male crabs with a carapace width >178 mm (or ~154 mm carapace length [CL]) may be taken legally (Orensanz et al., 1998). Crab pots or traps are used to capture red king crabs in this subsistence fishery. Harvest information has been available since 1995 for the Chiniak Bay area, which covers 321.0 km^2 and includes Womens Bay. With an area of 8.5 km^2, Womens Bay represents only about 2.5% of Chiniak Bay (Fig. 1). Harvest levels in Chiniak Bay from 1995 to 2012 ranged from 10 to 1178 crabs per year (median=66 crabs per year) (ADFG)[1] (Fig 2), which would indicate a low exploitation rate.

The population of red king crab in Womens Bay is not surveyed discretely, and no direct estimate of this population is available. However, the Kodiak district as a whole is surveyed by the Alaska Department of Fish and Game during its westward region trawl survey, when data are collected for estimates of the population size of red king crab and southern Tanner crab (*Chionoecetes bairdi*) in the northeast section of the Kodiak district, which includes Womens Bay (Fig. 1). For that survey ~90 tows are conducted, each 1.85 km long, in the northeast section of the Kodiak district with a 400-mesh eastern otter trawl constructed of 8.9-cm mesh in the body and 3.2-cm mesh in the codend to estimate population size by using the area-swept method (for complete survey methods and design, see Spalinger[2]).

Over the period of 1991–2012, estimates of the size of the population of red king crab in the northeast section have been low, ranging from about 160,000 to 0 (median=9500 crabs) (Fig. 2); these estimates are not precise because red king crabs typically are caught only at a few stations (Spalinger[2]). Our study area in Womens Bay accounts for <1% of the northeast section, a total area of 1978.5 km^2; therefore, the population in Womens Bay is likely a small proportion of the population estimated for this region.

Materials and methods

Our study is based on a 17-year data set, from 1991 to 2008, of tracking red king crab in Womens Bay with acoustic tags. Crabs were tracked during other projects where behavior and habitat use by red king crab were examined (Dew et al., 1992; Dew and McConnaughey, 2005; Dew, 2010) and were found primarily in pods, which are aggregations of crabs (Dew, 1990). Red king crabs (identified per Donaldson and Byersdorfer, 2005) were captured by divers throughout Womens Bay, and acoustic tags (Sonotronics; Tucson, AZ[3]) were affixed to each crab's carapace with marine grade epoxy. Only active, healthy-looking crabs were used, and crabs typically were new-shell (i.e., they had recently molted).

Crabs were released from the surface at the same location where they were captured (Fig. 1). Tags emitted unique acoustic sequences, allowing for the identification and tracking of individual crabs, and tracking was performed from the surface with a Sonotronics USR-4D surface acoustic receiver deployed from a boat. Each time a crab was located, the position of the vessel at the sea surface above the crab was recorded with a GPS unit. Accuracy of the boat's location in relation to the crab's location was generally about 40 m and was dependent on depth and weather. Crabs also were tracked with a Datasonics DPL-275A, underwater acoustic dive receiver (Teledyne Benthos, North Falmouth, MA), which allows divers to use acoustic signals to locate tags in situ. Crabs were located on the seafloor by scuba divers, and data were collected on the behavior and habitat of all live, tagged crabs, and any closely aggregated crabs; data included whether crabs were trapped alive in ghostfishing gear.

We classified the final condition of all crabs that had been tagged, including crabs no longer attached to their tag, and recorded the status of unrecovered tags in the following manner. When a tag was found on a complete, newly shed carapace, the final condition of the crab was classified as "molted." When a tag was found attached to a dead or partially eaten crab, final condition of the crab was classified as "dead." When the condition of the crab could not be determined with any confidence, its condition was classified as "unknown." Tags that could not be located from the surface were recorded as "lost," indicating either that the tag had run out of power or had malfunctioned or that the crab had moved into an area where it could not be tracked. Because we tracked all tagged crabs until they died, molted, or became lost, no tagged crabs had their final condition classified as live (see the last paragraph of this section). When a crab was classified as dead, the cause of death was ascertained when possible. Ghostfishing-induced mortality (hereafter termed "ghostfishing mortality") was recorded when that crab was found dead in ghost-

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[1] ADFG (Alaska Department of Fish and Game). 2012. Kodiak shellfish subsistence database. [Data available upon request from ADFG, 351 Research Ct, Kodiak, AK 99615-7400.]

[2] Spalinger, K. 2009. Bottom trawl survey of crab and groundfish: Kodiak, Chignik, South Peninsula, and Eastern Aleutians Management Districts, 2008. Fishery Management Report 9-25, 121 p. Alaska Department of Fish and Game, Anchorage, AK.

[3] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

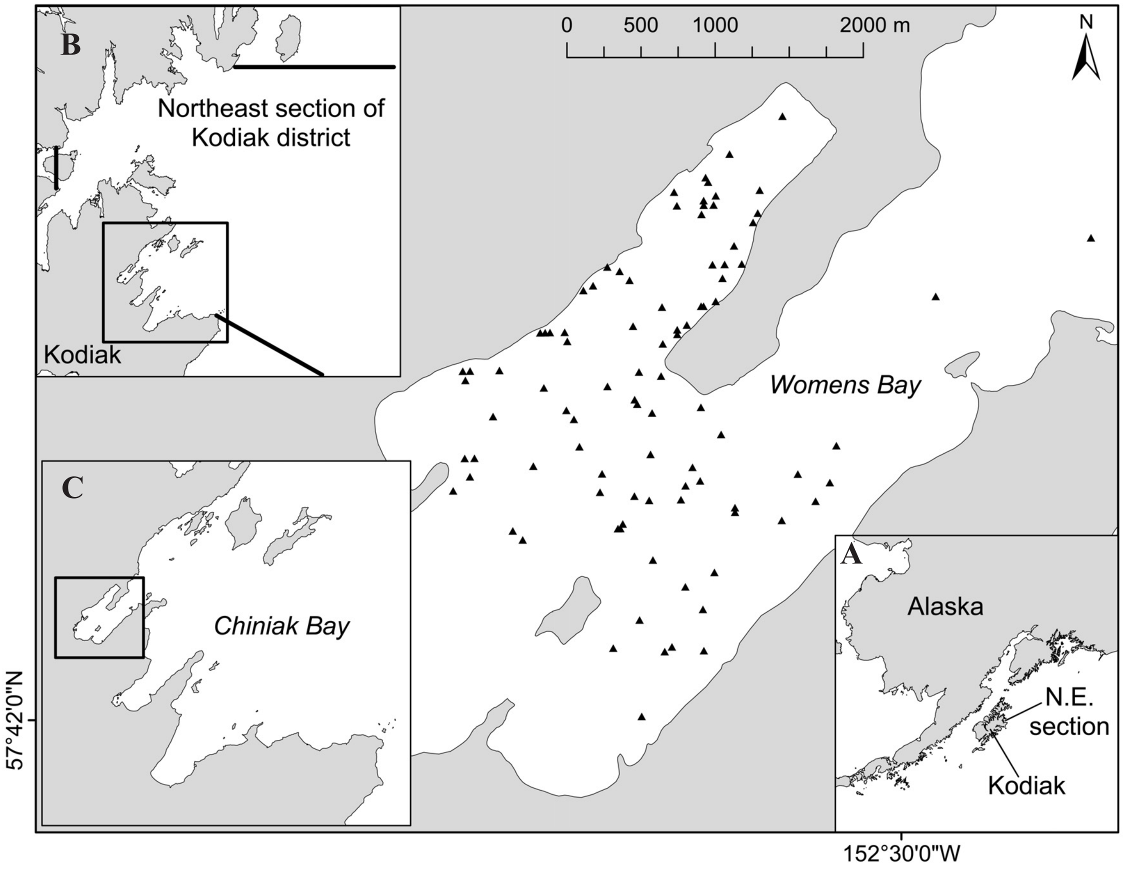

Figure 1

Map showing study area and sites (▲) where tagged red king crabs (*Paralithodes camtschaticus*) were released in Womens Bay, Kodiak Island, Alaska, during this study in association with other projects over the period of 1991–2008: (**A**) Alaska and Kodiak Island, (**B**) the northeast section of the Kodiak district, as defined for the westward region trawl survey of the Alaska Department of Fish and Game, and (**C**) Chiniak Bay. The southwestern portion of the bay is a shallow area where the red king crab does not occur, and no crabs were released there. In Inset A, lines are drawn to indicate Kodiak Island and the northeast section (N.E. section). In Inset B, lines show boundaries of the northeast section (adapted from the Fishery Management Report 09-25 by K. Spalinger published in 2009 by the Alaska Department of Fish and Game) and the rectangle around Chiniak Bay shows the extent of Inset C. In Inset C, the rectangle around Womens Bay shows the extent of the main map

fishing gear. On one occasion, 3 crabs released on the same day all died almost immediately for no apparent reason, and each of these crabs was recorded as a handling-induced mortality (hereafter "handling mortality"). There was no evidence of any latent handling mortality for other crabs in this study. All other causes of death were classified as "other mortality." One tag became detached from its crab because the epoxy failed to adhere to the carapace and was classified as a "tagging failure." Occasionally, surface tracking located a tag that had stopped moving for a long period of time and was not recovered because either it was in an unsuitable diving location or there were other logistical concerns (e.g., ice cover). Such tags were denominated as "derelict." Generally, all tagged crabs were tracked and diver observations were made weekly on a subset of tags, but effort varied with season, weather, and availability of field personnel.

When divers discovered ghost pots, both during this and other projects (effort on other projects varied throughout the study period) in Womens Bay, they made notes that included the type of gear, whether it was found intact or upside down, and the approximate number and species of crabs entangled or entrapped in the gear. Documentation of whether the pot was upside down is important because Dungeness pots have legally mandated biodegradable release mechanisms on their tops (ADFG[4]), making release ineffective if the

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[4] ADFG (Alaska Department of Fish and Game). 2011. Shellfish gear requirements. Accessed September 2011. http://www.adfg.alaska.gov/index.cfm?adfg=personalusebyareasoutheastGear.main.

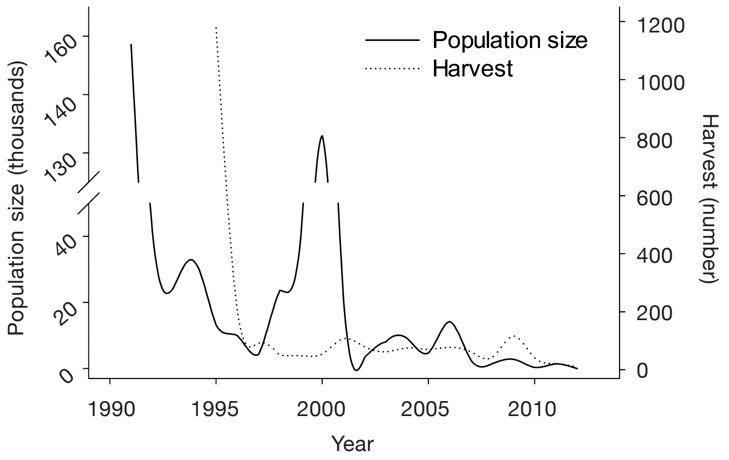

Figure 2

Population size and harvest levels for red king crab (*Paralithodes camtschaticus*) in 1991–2012. Population size (in thousands of individuals) is for the northeast section of the Kodiak district, as defined for the westward region trawl survey of the Alaska Department of Fish and Game, and harvest levels are for Chiniak Bay. The study area, Womens Bay, is part of Chiniak Bay, which is in turn part of the northeast section of Kodiak district (Fig. 1). Data used in this graph came from Alaska Department of Fish and Game reports on bottom trawl surveys of crabs and groundfishes conducted in 1991–2012: Technology Fishery Reports 93-16, 93-17 and Regional Information Report 4K95-1 by D. Urban, and Fishery Management Reports 05-48 and 13-27 by K. Spalinger.

pot is flipped over. Field personnel made observations on both ghost and actively fishing pots to determine the likely causes of pot loss in Womens Bay. Divers routinely disabled all ghost pots that they discovered, rendering them incapable of catching animals, and they released all trapped animals.

We assessed the effects of ghost fishing on the population of red king crab in Womens Bay by modeling the rate of tag loss. We assumed, on the basis of hundreds of hours of in situ observations during which we did not see any differences in behavior between tagged and untagged crabs, that tagged animals were representative of the population (except in cases of handling mortality, which we quantified and explicitly corrected for) and that tagging did not change behavior (Pollock et al., 1991). In particular, in the context of this study, we assumed that tagged crabs did not suffer higher natural or fishing mortality, that they did not molt at a higher rate, and that they were no more likely to enter a crab pot than were untagged crabs. Given these assumptions, the mortality rate of the population as a whole would be similar to the calculated mortality rates of tagged crabs (Pollock et al., 1991; Lambert et al., 2006).

As part of our determination of mortality rates, we estimated the number of days between the release date and date of final condition (e.g., the day a crab molted or died). If a tag had been located from the surface at the same position several times, then a dive was performed to determine the final condition of a crab. In most of these cases, we used the date from the second time the crab was located at that same position as the estimated date of final condition. When the time between the surface locations was greater than a month, the date half-way between them was used. If there was no indication that the crab had remained in the same location for a length of time (fewer than 2 surface observations at the same location), we used the day of the final dive observation as the end date.

We fitted the data using maximum likelihood to an exponential loss model assuming a binomial distribution such that

$$P = e^{-rt},$$

where P = the probability that a tagged crab molted, died, or was lost;
r = the instantaneous loss rate; and
t = the time in days.

We calculated the loss rate due to each cause (i.e., molting, ghostfishing mortality, handling mortality, or tag detachment, other mortality, and tag malfunction) with the proportional number of crabs in each category. For example, the rate of mortality from ghost fishing was calculated as

$$r_{GF} = rp_{GF},$$

where r_{GF} = the rate of crab loss due to ghost fishing;
r = the overall loss rate calculated above; and
p_{GF} = the proportion of crabs in this study that died from ghost fishing.

We assumed that tagged crabs with a condition classified as "unknown" had either died from causes other than ghost fishing (e.g., fishing mortality and poaching) or had molted. Additionally, we assumed that crab with tags classified as "derelict" had died from causes other than ghost fishing, had molted, or had been killed in ghostfishing gear. Therefore, we divided the crabs with unknown conditions or derelict tags into categories on the basis of the relative observed frequency of each cause of mortality. Tags classified as lost were kept as a separate category because no data on what happened to the tag were available.

Divers found 20 tagged crabs and hundreds of closely aggregated crabs alive in intact ghost pots and released them. In most cases, it was not possible to record the numbers of untagged live crabs released by divers because of the large numbers of those crabs and because visibility was greatly limited by silt disturbed from pot handling; therefore, only rough estimates were made. Two of the tagged crabs that were released later died in another crab pot. Given the length of time the crabs were likely in the pots, it is unlikely that many of these crabs would have escaped alive (High and Worlund, 1979).

To estimate an upper and lower limit for the mortality rate of crabs from ghost fishing in the absence of diver interference, we calculated the loss rates with the assumption that none of the crabs released from pots would have died (conservative estimate) and with the assumption that all of them would have died (upper estimate). For the conservative estimate, we used the date the crab died, molted, or was lost after having been released as the date of the final condition. For the upper estimate, we classified the crab as a "ghostfishing mortality" and used the date the crab was released from the pot as the date of the final condition of the crab, as if the crab had been found dead in the pot. We performed a logistic regression, using sex as a factor and CL as a covariate, to examine whether size or sex of a crab made it more likely that it would be caught or killed in ghostfishing gear.

Results

The size of tagged crabs ranged from 42 to 162 mm CL (mean=100 mm CL). Of the 192 crabs tagged over the course of multiple studies, 90 were female and 102 were male. The number of crabs tagged each year ranged from 2 (in 2007 and 2008) to 20 (in 1996) and averaged 11 crabs per year. Crabs were tracked for an average of 147 days and a maximum of 468. The total number of observations on tagged crabs was 3300. Molting was the most common final condition of a tagged crab, followed by unknown condition (Table 1). Three crabs migrated out of Womens Bay during the project, but they were tracked and their final condition was determined as was done for all other tagged crabs. Thirteen crabs died in ghostfishing gear, and 13 more crabs had other sources of mortality.

Table 1

Final conditions determined in this study for the 192 red king crabs (*Paralithodes camtschaticus*) or their tags that were tracked by acoustic tagging in association with other projects over the period of 1991–2008 in Womens Bay, Kodiak Island, Alaska. "Molted" means the tagged crab molted. "Unknown" means the tag was recovered by divers but it could not be determined if the tagged crab had molted or died. "Lost" means the tag could not be located from the surface. "Derelict" means the tagged crab either molted or died as evidenced by the fact the tag stopped moving but the condition was not determined by diving. "Other mortality" means the tagged crab died from a cause other than ghost fishing. "Ghostfishing mortality" means the tagged crab died in ghostfishing gear. "Handling mortality" means the tagged crab died as a result of the tagging process. "Tag failure" means the tag failed to adhere to the tagged crab's carapace.

Final condition	Number	Percentage
Molted	76	39.6
Unknown	48	25.0
Lost	22	11.5
Derelict	16	8.3
Other mortality	13	6.8
Ghostfishing mortality	13	6.8
Handling mortality	3	1.6
Tag failure	1	0.5

Known sources of mortality included predation by sea otters (3 crabs) and an octopus (1 crab) and likely poaching by humans (the tags of 2 crabs below the legal-size limit were returned to researchers with implausible stories about how the tags were obtained). Legal fishing did not account for a single mortality of a tagged crab during this study. Of the 13 crabs that died in ghostfishing gear, 12 crabs were caught in ghost pots and 1 crab was found in a ghost gill net. As for all the crabs caught in ghostfishing gear and released alive by divers, they all were found in the same type of gear: ghost pot.

Crabs that died in ghostfishing gear ranged from 69 to 160 mm CL and included 4 ovigerous females. Crabs caught and released by divers ranged from 66 to 141 mm CL and included 5 ovigerous females. One difference between the crabs that died and the crabs that were released was the number of days between the time when the crab was caught in the trap (as estimated from surface tracking) and the time when a

Table 2

Types of ghost pots found in Womens Bay, Kodiak Island, Alaska, by divers over the period of 1991–2008 and classification according to whether a pot was still intact and whether it was found upright or upside down. "Unknown" indicates that the type of pot could not be assessed. "Unknown condition" indicates that the divers could not determine if the pot was intact.

Type	Number found	Number intact	Percentage intact (%)	No. found upside-down	Unknown condition
Dungeness	70	46	66	8	2
Webbed	42	30	71	2	2
Home made	20	10	50	2	1
Store bought	7	3	43	1	2
Unknown	4	0	0	0	2
Total	143	89	62	13	9

dive was performed. The amount of time crabs spent in the trap averaged 38 (standard deviation [SD] 23 days) for crabs that died and 10 (SD 8 days) for crabs that were alive when released. The red king crab accounted for the majority of the organisms found in crab pots. Rarely found species included sculpins (*Myoxocephalus* spp.), southern Tanner crab, and Dungeness crab (*Metacarcinus magister*; *sensu* Schram and Ng, 2012).

Over the study period in Womens Bay, divers located 143 pots, of which 60 were found during the tracking of tagged crabs and 83 were found during other projects (Table 2). Of these pots, about half were Dungeness crab pots, which have the shape of a squat cylinder and a frame of steel covered with a mesh of stainless steel. Steel-frame pots, which are large, commercial-size pots with steel frames constructed in the shape of a pyramid, cone, or rectangle and which are covered in webbing that is usually made of nylon, were the next most frequently encountered type of pot, followed by homemade pots. Only a few sport pots, which are smaller, light-weight pots that are commercially produced and easily retrievable by hand, and pots of unknown type were found. Of the crab pots that were encountered, 62% were intact, indicating that those pots lacked a biodegradable release and were capable of ghost fishing. Additionally, other than the Dungeness crab pots, most of the pots lacked escape rings. Likely reasons for pot loss, determined on the basis of field observations, included release of a pot after a line was cut by boat propellers; entanglement of a pot in lines that were dragged by commercial barge towing bridals, sinking of a float due to biofouling on the lines, and breakage of a line by ice.

The conservative estimate of the overall rate of loss of tagged crabs from all sources, including sources of mortality, was about 10% less than the upper estimate; however, the upper estimate of the predicted mortality rate from ghost fishing was nearly 300% higher than the conservative estimate of the predicted mortality rate from ghost fishing (Table 3). Other sources of loss did not vary substantially between the 2 estimates. Overall annual mortality estimated from tagging data ranged from 40% to 56% for the conservative and upper estimates (Fig. 3). Using the calculated rate of mortality of tagged crabs in Womens Bay and applying it to the whole population of red king crab in this bay, we estimated that ghost fishing killed between 16% and 37% of the population per year, according to our conservative and upper estimates (Fig. 3).

Table 3

Instantaneous loss rates for tagged red king crabs (*Paralithodes camtschaticus*) and tags in Womens Bay, Kodiak Island, Alaska, during the period of 1991–2008. The conservative estimate for ghostfishing mortality was determined on the basis of counts of crabs that died in ghostfishing gear. For the upper estimate, we assumed that all crabs caught in ghost-fishing gear and released by divers would have died. The estimate for experimental error includes handling mortality and tags that fell off crabs. The "All" category represents all sources of crab loss and is the parameter fitted by the exponential decay model (see the model in the *Materials and methods* section of the text for details). Standard errors of the mean are presented in parentheses.

	Loss rate (days^{-1})	
Source of loss	Conservative	Upper
All	0.00709 (0.00003)	0.00782 (0.00004)
Molting	0.00476 (0.00017)	0.00466 (0.0003)
Ghostfishing mortality	0.00056 (0.00007)	0.00147 (0.00023)
Other mortality	0.00081 (0.00017)	0.00075 (0.00017)
Lost tag	0.00081 (0.00016)	0.00077 (0.00017)
Experimental error	0.00015 (0.00024)	0.00016 (0.00008)

Logistic regression revealed that neither size nor sex affected the probability of a tagged crab being killed or caught in ghostfishing gear, although there was a nonsignificant trend (*P*=0.055; Table 4) for larger (>140 mm CL) tagged crabs than for the smallest (40–60 mm CL) crabs to be killed in ghostfishing gear; however, this trend may be driven by the low number of crabs tagged in the smallest and largest size categories (Table 4, Fig. 4). Because we did not observe any ghostfishing mortality for crabs with CL ≤60 mm, we restrict our inference about the effect of ghost fishing at the population level to crabs with CL >60 mm. Although our data suggest that the ghostfishing mortality rate for the largest crabs (>140 mm CL; this size category includes legal-size crabs) is higher than our average rate for crabs of all sizes, we take the conservative approach by applying a constant rate of ghostfishing mortality to all crabs >60 mm CL because of our lower sample size for crabs in the largest size category.

Discussion

The 17-year data set used in our study allowed us to estimate the effect of ghost fishing on a local population of red king crab. The results of this study indicate that ghost fishing in Womens Bay was responsible for more mortality of red king crabs with CL >60 mm than any other single observed cause of mortality observed during our study. Indeed, our data provide evidence that the rate of mortality from ghost fishing may be almost double the rate from all other sources of mortality combined (for caveats to this assertion, see the discussion later in this section on mortality associated with molting). These results indicate that ghost fishing has a large, negative effect on the population of red king crab in Womens Bay and that changes in regulations designed to minimize ghost fishing or in their enforcement may be warranted.

Although many studies have quantified the effects of ghost fishing, most estimate the number of animals killed per unit of time (e.g., Breen, 1987; Hebert et al., 2001), the number killed per pot per unit of time (e.g., Bullimore et al., 2001; Al-Masroori et al., 2004; Campbell and Sumpton, 2009), or simply the number of crabs caught per pot (e.g., Stevens et al., 2000; Havens et al., 2008). These studies focus on following or recovering lost gear and examining catches and mortality over time on a local population. However, in scaling up to estimate effects on larger or commercially targeted populations, assumptions or estimates of the number of pots lost and the population size are required. By following the fates of individuals in the Womens Bay population, we could estimate with precision the actual mortality rate at the population level, assuming tags do not alter crab behavior. A drawback of this approach, however, is that it applies only to Womens Bay and is not easily extrapolated to other areas. Still, this problem is one shared by all studies of ghost fishing.

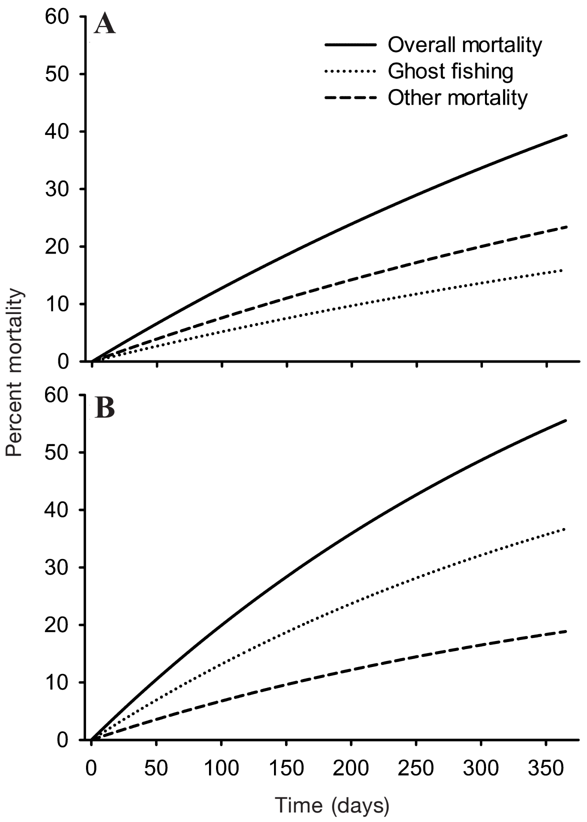

Figure 3

Predicted percent mortality over a year for red king crab (*Paralithodes camtschaticus*) in Womens Bay, Kodiak Island, Alaska. "Overall mortality" is the total mortality from all sources and is the sum of ghostfishing mortality and other mortality. "Ghost fishing" is the percentage of crabs that are killed in ghostfishing gear. "Other mortality" includes all other sources of mortality, including predation and fishing. (**A**) Conservative estimates of mortality; only crabs that died in ghostfishing gear were included in estimates of ghostfishing mortality. (**B**) Upper estimates of mortality; all crabs caught in intact ghostfishing gear were included in these estimates of ghostfishing mortality.

Our conservative estimate of ghostfishing mortality is precise, and because of the narrow definition for crabs considered to have died in pots, it represents the absolute minimum effect that ghost fishing had on the population of red king crab in Womens Bay during our study. However, it is likely a large underestimate. Because this study was not originally intended to document the effects of ghost fishing, divers actively decreased the effects of ghost fishing by releasing trapped crabs and disabling ghost pots. How many of the crabs caught in pots would have died is difficult to determine. Although escape rates for red king crabs from intact commercial red king crab pots may be up

Table 4

Results of logistic regression used to examine effects of size (carapace length) and sex on the likelihood of death or capture in ghostfishing gear for red king crabs (*Paralithodes camtschaticus*) in Womens Bay, Kodiak Island, Alaska, during the period of 1991–2008. Z=Z-score; P=probability. "Size" is the carapace length of the crab.

Parameter	Estimate	Standard error	Z	P
Crabs that died in ghostfishing gear				
Constant	–4.69	1.30	–3.61	0.000
Size	0.02	0.01	1.92	0.055
Sex (female)	–0.22	0.61	–0.37	0.714
Crabs that were caught in ghostfishing gear				
Constant	–2.57	0.82	–3.12	0.002
Size	0.01	0.01	0.89	0.373
Sex (female)	0.63	0.40	1.58	0.114

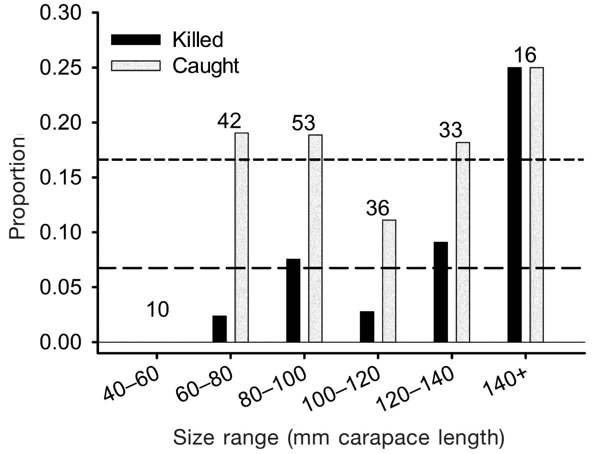

Figure 4

Proportion of tagged red king crabs (*Paralithodes camtschaticus*) that died (black bars) or were caught (gray bars) in ghostfishing gear in Womens Bay, Kodiak Island, Alaska, during the period of 1991–2008. Note that no crabs with carapace lengths between 40 and 60 mm were caught or killed. The number above each set of bars represents the total number of crabs in each size category. The line with the long dashes indicates the overall proportion of tagged crabs killed in ghostfishing gear, and the line with the short dashes indicates the overall proportion caught in ghostfishing gear.

to 90% (High and Worlund, 1979) and mortality of crabs trapped in such pots may be no higher than 17% (Godøy et al., 2003), these rates of escape and mortality do not reflect rates for most of the pots in our study because many of the pots observed in our study targeted the Dungeness crab.

Current regulations in Alaska require escape rings on Dungeness crab pots to be 121 mm, smaller than the 159 mm required for red king crab pots (ADFG[4]), but most of the pots found during our study that were of a type other than the Dungeness crab pot did not have escape rings. Therefore, we would expect much lower escape rates for red king crabs caught in the pots observed in this study. Estimates for mortality rates have been much lower for crabs trapped in red king crab pots than for crabs caught in many other pot types: 31–46% mortality of blue swimmer crabs (*Portunus pelagicus*) in blue swimmer crab pots (Campbell and Sumpton, 2009), 52% of Dungeness crabs in Dungeness crab pots (Breen, 1987), and 95% mortality of snow crabs (*Chionoecetes opilio*) in snow crab pots (Hebert et al., 2001).

Given the relatively small escape rings of pots designed for much smaller crab species and the absence of escape rings in the pots observed in this study, the majority of red king crabs found trapped in pots likely would have been unable to escape and eventually would have died. Results from our study suggest that red king crabs ≤60 mm CL are less likely to be caught or killed in pots than crabs of other sizes and that crabs >140 mm CL are more likely than crabs ≤140 mm to become trapped or to die in pots; however, these findings were not statistically significant and may have been driven to some extent by small sample sizes for crabs in the largest and smallest size categories. Although smaller crabs probably are more likely to escape from pots (High and Worlund, 1979), our data indicate that crabs >60 mm CL are vulnerable to the types of ghost pots observed in this study.

Escape of red king crabs from pots is asymptotic over time, and the number of crabs escaping levels off at about 8 days (High and Worlund, 1979). We estimated that only 8 of the 20 crabs released from pots had been trapped for less than 8 days. If the remaining 12 crabs had been able to escape, then they probably would have done so before they were rescued. Additionally, divers in this study actively disabled 89 intact pots that would otherwise have continued to ghost fish, likely substantially lowering the effect of ghost fishing in Womens Bay. Given these observations, we believe that the true mortality rate from ghostfishing gear is somewhere between our conservative and upper estimates and is most likely closer to the upper estimate.

Although our estimate of the rate of mortality of red king crabs from sources other than ghost fishing is reasonably precise, it is almost certainly an underestimate because it does not account for mortalities that may occur during molting, which is physiologically stressful for crustaceans (Leffler, 1972), or shortly after molting, when they are particularly vulnerable to predation (Shirley et al., 1990; Ryer et al., 1997; Marshall et al., 2005). However, for the intermolt period of red king crab, our estimate is likely an accurate picture of mortality. Roughly a third of all crabs that died suffered predation, a sixth of them were poached, and the cause of death could not be determined for the remaining half. Ironically, no tagged male crabs of legal size were taken by fishermen in this study; no doubt, zero fishing mortality was due in part to the fact that few legal-size crabs were tagged and to the low fishing mortality for this species in the study area (Fig. 2). During another study in Bristol Bay, instantaneous mortality rates estimated for the red king crab ranged from 0.02 to 1.75 year^{-1} and most estimates ranged between 0.02 and 1.00 year^{-1} (reviewed in Zheng, 2005). Our estimates for rates of mortality from sources other than ghost fishing were 0.30 and 0.27 year^{-1}, values that fall well within that range.

The estimated mortality rate from ghost fishing is high enough to have a devastating effect on the population of red king crab in Womens Bay. A 60-mm-CL crab is at least 2 years from attaining reproductive maturity (Weber, 1967), and females must brood their eggs for a year after attaining maturity before they can reproduce successfully for the first time (Stevens and Swiney, 2007). Therefore, on the basis of our conservative and upper estimates of ghostfishing mortality (16–37% per year), we estimate, with the assumption that crabs become vulnerable to ghost fishing at a size of 60 mm CL, that 29–60% of male crabs and 41–75% of female crabs were killed in ghostfishing gear before they were able to reproduce for the first time during our study.

To put those high mortality rates in context, the target rate for fishing mortality designed to maintain a healthy stock size in Bristol Bay is <15% of the mature male biomass and only negligible numbers of nontargeted mature female and immature crabs are allowed to be taken as bycatch (Zheng and Siddeek[5]). Because the fecundity of females increases more than an order of magnitude with crab size (Swiney et al., 2012), ghost fishing keeps many females from reaching their full reproductive potential by killing them when they are small and have relatively low fecundity; moreover, because ghost fishing indiscriminately removes both immature and mature crabs, including ovigerous females, it compounds its effects as it reduces the reproductive capacity of the local population, as well as the size of the local population itself.

How typical Womens Bay may be among areas in the Gulf of Alaska is unknown. Its proximity to the city of Kodiak makes it a popular site for sport, subsistence, and commercial fisheries. The greater fishing effort and boat traffic in this bay, compared with such activities in other areas, has likely led to a higher rate of fishing gear loss. Additionally, participants in the sport and subsistence fisheries may be less likely to know about or comply with the requirements for escape mechanisms on pots. Supporting this premise, homemade pots found in our study were almost certainly not used for commercial purposes, and their structure was frequently noncompliant with established requirements for escape rings and biodegradable release. Enforcement of regulations in the sport and subsistence fisheries also probably is less stringent than it is in the commercial fishery because there are far fewer commercial fishermen to monitor (who fish with numerous pots per boat) than subsistence fishermen (who fish with few pots per boat). It is likely that other coastal bodies of water with high densities of crabs near population centers in Alaska have similar rates of ghost fishing and that bodies of water farther from human population centers have a lower rate.

If ghost fishing does have the profound effect that is indicated by our data on the population of red king crab in Womens Bay, measures to reduce ghost fishing are warranted. Of the different types of gear, crab pots were the major cause of ghostfishing mortality; in contrast, gill nets were responsible for only one death. Therefore, efforts to reduce ghost fishing on the red king crab should focus on pots (although removing nets may be a priority for other species, such as marine birds [Good et al., 2009; 2010]). Existing ghost pots can be located by side-scan sonar and removed by grappling (Stevens et al., 2000) and their threat eliminated as a result. Removal of ghost pots would be most effective in shallow areas of high fishing intensity, such as Womens Bay.

The observed effects of ice deserve a special note. Womens Bay frequently had a fresh water lens from various freshwater sources (Long, 1972) that can freeze during the winter. Ice embedded pot floats and when the ice broke up, pots were dragged into deeper water, where their float lines were not long enough to reach the surface, or they were dragged into shallow water, where pot owners were not likely to look for them. The strain of being dragged across the bottom of the bay could have caused lines to break. Additionally, tides or wind moved thin sheets of ice that abraded floats and lines and caused them to sink. Ice and boats dragged pots across the bottom of the bay, flipping some of them upside down or partially burying them—outcomes that, in the case of Dungeness crab pots, rendered the escape mechanism, if present, ineffective. If areas affected by ice were closed during months when ice was a concern, the rate of pot loss could be reduced. This closure would not substantially affect fishing because crab pots cannot be checked during times of ice cover.

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[5] Zheng , J., and M. S. M. Siddeek. 2010. Bristol Bay red king crab stock assessment in spring 2010. *In* Stock assessment and fishery evaluation report for the king and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. 2010 Crab SAFE, p. 135–246. North Pacific Fishery Management Council, Anchorage, AK. [Available from http://www.npfmc.org/wp-content/PDFdocuments/resources/SAFE/CrabSAFE/CRABSAFE2010.pdf.]

Such closures also would reduce the number of pots abandoned and left out long enough to have their floats sunk by marine-fouling organisms.

Current regulations allow the tie-down of a pot lid to be equipped with cotton twine that will decay and release the lid after a length of time (ADFG[4]). However, we observed that pots can be flipped upside down when lost, rendering this escape mechanism unworkable. If Dungeness crab pots were required to have a sidewall release as an escape mechanism, this requirement would greatly reduce this problem. To reveal further means of reducing ghost fishing, more experimental work is needed to examine the effectiveness of various release mechanisms for allowing target species and other species to escape pots (Matsuoka et al., 2005).

Conclusions

Ghost fishing is an entirely wasteful source of mortality in aquatic systems. Although lost fishing gear is an inevitable consequence of fishing, it can become a substantial drain on both fished and nonfished species. In Womens Bay, ghost fishing, primarily by crab pots, is a source of mortality that may have a strong negative effect upon the population by killing 16–37% of the population per year. This negative effect could be decreased through implementation of measures to reduce the loss rate of crab pots and to ensure that pots do not continue to fish long after they are lost.

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Literature cited

Al-Masroori, H., H. Al-Oufi, J. L. McIlwain, and E. McLean.
2004. Catches of lost fish traps (ghost fishing) from fishing grounds near Muscat, Sultanate of Oman. Fish. Res. 69:407–414.

Baeta, F., M. J. Costa, and H. Cabral.
2009. Trammel nets' ghost fishing off the Portuguese central coast. Fish. Res. 98:33–39.

Breen, P. A.
1987. Mortality of Dungeness crabs caused by lost traps in the Fraser River Estuary, British Columbia. N. Am. J. Fish. Manage. 7:429–435.
1990. A review of ghost fishing by traps and gillnets. *In* Proceedings of the second international conference on marine debris; Honolulu, 2–7 April 1989 (R. A. Shomura and M. L. Godfrey, eds.), p. 571–599. NOAA Tech. Memo. NOAA-TMSWFSC–154.

Bullimore, B. A., P. B. Newman, M. J. Kaiser, S. E. Gilbert, and K. M. Lock.
2001. A study of catches in a fleet of "ghost-fishing" pots. Fish. Bull. 99:247–253.

Campbell, M. J., and W. D. Sumpton.
2009. Ghost fishing in the pot fishery for blue swimmer crabs *Portunus pelagicus* in Queensland, Australia. Fish. Res. 95:246–253.

Dew, C. B.
1990. Behavioral ecology of podding red king crab, *Paralithodes camtschatica*. Can. J. Fish. Aquat. Sci. 47:1944–1958.
2010. Podding behavior of adult king crab and its effect on abundance-estimate precision. *In* Biology and management of exploited crab populations under climate change (Kruse, G. H., G. L. Eckert, R. J. Foy, R. N. Lipcius, B. Sainte-Marie, D. L. Stram, and D. Woodby, eds.), p. 129–151. Alaska Sea Grant College Program, Univ. Alaska Fairbanks, Fairbanks, AK.

Dew, C. B., and R. A. McConnaughey.
2005. Did trawling on the brood stock contribute to the collapse of Alaska's king crab? Ecol. Appl. 15:919–941.

Dew, C. B., P. A. Cummiskey, and J. E. Munk.
1992. The behavioral ecology and spatial distribution of red king crab and other target species: implications for sampling design and data treatment. *In* Proceedings of the international crab rehabilitation and enhancement symposium; Kodiak, AK (L. White and C. Nielsen, eds.), p. 39–67. Fisheries Rehabilitation, Enhancement and Development Division, Alaska Department of Fish and Game, Juneau, AK.

Donaldson, W., and S. Byersdorfer.
2005. Biological field techniques for lithodid crabs. Alaska Sea Grant College Program Report AK-SG-05-03, 82 p. Univ. Alaska Fairbanks, Fairbanks, AK.

Erzini, K., L. Bentes, R. Coelho, P. G. Lino, P. Monteiro, J. Ribeiro, and J. M. S. Goncalves.
2008. Catches in ghost-fishing octopus and fish traps in the northeastern Atlantic Ocean (Algarve, Portugal). Fish. Bull. 106:321–327.

Gerrodette, T., B. K. Choy, and L. M. Hiruki.
1990. An experimental study of derelict gillnet fragments in the central Pacific Ocean. *In* Proceedings of the second international conference on marine debris; Honolulu, 2–7 April 1989 (R. A. Shomura and M. L. Godfrey, eds.), p. 600–614. NOAA Tech. Memo. NOAA-TMSWFSC-154.

Godøy, H., D. M. Furevik, and S. Stiansen.
2003. Unaccounted mortality of red king crab (*Paralithodes camtschaticus*) in deliberately lost pots off northern Norway. Fish. Res. 64:171–177.

Good, T. P., J. A. June, M. A. Etnier, and G. Broadhurst.
2009. Ghosts of the Salish Sea: threats to marine birds in Puget Sound and the Northwest Straits from derelict fishing gear. Mar. Ornithol. 37:67–76.
2010. Derelict fishing nets in Puget Sound and the Northwest Straits: patterns and threats to marine fauna. Mar. Pollut. Bull. 60:39–50.

Havens, K. J., D. M. Bilkovic, D. Stanhope, K. Angstadt, and C. Hershner.
2008. The effects of derelict blue crab traps on marine organisms in the lower York River, Virginia. N. Am. J. Fish. Manage. 28:1194–1200.

Hebert, M., G. Miron, M. Moriyasu, R. Vienneau, and P. DeGrace.
2001. Efficiency and ghost fishing of snow crab (*Chionoecetes opilio*) traps in the Gulf of St. Lawrence. Fish. Res. 52:143–153.

High, W. L., and D. D. Worlund.
1979. Escape of king crab, *Paralithodes camtschatica*, from derelict pots. NOAA Tech. Rep. NMFS SSRF-734, 11 p.

Kaiser, M. J., B. Bullimore, P. Newman, K. Lock, and S. Gilbert.
1996. Catches in 'ghost fishing' set nets. Mar. Ecol. Prog. Ser. 145:11–16.

Laist, D. W.
1996. Marine debris entanglement and ghost fishing: a cryptic and significant type of bycatch? *In* Solving bycatch: considerations for today and tomorrow, p. 33–39. Proceedings of the solving bycatch workshop; Seattle, 25–27 September 1995. Alaska Sea Grant College Program Report AK-SG-96-03. Univ. Alaska Fairbanks, Fairbanks, AK.

Lambert, D. M., J. M. Hoenig, and R. N. Lipcius.
2006. Tag return estimation of annual and semiannual survival rates of adult female blue crabs. Trans. Am. Fish. Soc. 135:1592–1603.

Leffler, C.
1972. Some effects of temperature on the growth and metabolic rate of juvenile blue crabs, *Callinectes sapidus*, in the laboratory. Mar. Biol. 14:104–110.

Long, E. R.
1972. Studies of marine fouling and boring off Kodiak Island, Alaska. Mar. Biol. 14:52–57.

Marshall, S., K. Warburton, B. Paterson, and D. Mann.
2005. Cannibalism in juvenile blue-swimmer crabs *Portunus pelagicus* (Linnaeus, 1766): effects of body size, moult stage and refuge availability. Appl. Anim. Behav. Sci. 90:65–82.

Matsuoka, T., T. Nakashima, and N. Nagasawa.
2005. A review of ghost fishing: scientific approaches to evaluation and solutions. Fish. Sci. 71:691–702.

Orensanz, J., J. Armstrong, D. Armstrong, and R. Hilborn.
1998. Crustacean resources are vulnerable to serial depletion—the multifaceted decline of crab and shrimp fisheries in the Greater Gulf of Alaska. Rev. Fish Biol. Fish. 8:117–176.

Paul, J., A. Paul, and A. Kimker.
1994. Compensatory feeding capacity of 2 brachyuran crabs, Tanner and Dungeness, after starvation periods like those encountered in pots. Alaska Fish. Res. Bull. 1:184–187.

Pollock, K. H., J. M. Hoenig, and C. M. Jones.
1991. Estimation of fishing and natural mortality when a tagging study is combined with a creel survey or port sampling. *In* Creel and angler surveys in fisheries management (D. Guthrie, J. M. Hoenig, M. Holliday, C. M. Jones, M. J. Mills, S. A. Moberly, K. H. Pollock, and D. R. Talhelm, eds.), p. 423–434. Am. Fish. Soc. Symp. 12, Bethesda, MD.

Ramirez-Rodriguez, M., and F. Arreguin-Sanchez.
2008. Fishing time and trap ghost fishing for *Cancer johngarthi* along the Baja California Peninsula's southwestern coast, Mexico. J. Shellfish Res. 27:1265–1269.

Ryer, C. H., J. van Montfrans, and K. E. Moody.
1997. Cannibalism, refugia and the molting blue crab. Mar. Ecol. Prog. Ser. 147:77–85.

Santos, M. N., H. J. Saldanha, M. B. Gaspar, and C. C. Monteiro.
2003. Hake (*Merluccius merluccius* L., 1758) ghost fishing by gill nets off the Algarve (southern Portugal). Fish. Res. 64:119–128.

Schram, F. R., and P. K. L. Ng.
2012. What is *Cancer*? J. Crust. Biol. 32:665–672.

Shirley, M. A., A. H. Hines, and T. G. Wolcott.
1990. Adaptive significance of habitat selection by molting adult blue crabs *Callinectes sapidus* (Rathbun) within a subestuary of central Chesapeake Bay. J. Exp. Mar. Biol. Ecol. 140:107–119.

Smolowitz, R.
1978. Trap design and ghost fishing: an overview. Mar. Fish. Rev. 40:2–8.

Stevens, B. G., and K. M. Swiney.
2007. Hatch timing, incubation period, and reproductive cycle for captive primiparous and multiparous red king crab, *Paralithodes camtschaticus*. J. Crust. Biol. 27:37–48.

Stevens, B. G., I. Vining, S. Byersdorfer, and W. Donaldson.
2000. Ghost fishing by Tanner crab (*Chionoecetes bairdi*) pots off Kodiak, Alaska: pot density and catch per trap as determined from sidescan sonar and pot recovery data. Fish. Bull. 98:389–399.

Swiney, K. M., W. C. Long, G. L. Eckert, and G. H. Kruse.
2012. Red king crab, *Paralithodes camtschaticus,* size-fecundity relationship, and interannual and seasonal variability in fecundity. J. Shellfish Res. 31:925–933.

Weber, D. D.
1967. Growth of the immature king crab *Paralithodes camtschatica* (Tilesius). Bull. Int. North Pac. Fish. Comm. 21:21–53.

Zheng, J.
2005. A review of natural mortality estimation for crab stocks: data-limited for every stock? *In* Fisheries assessment and management in data-limited situations (G. H. Kruse, V. F. Gallucci, D. E. Hay, R. I. Perry, R. M. Peterman, T. C. Shirley, P. D. Spencer, B. Wilson, and D. Woodby, eds.), p. 595–612. Alaska Sea Grant College Program Report AK-SG-05-02, Univ. Alaska Fairbanks, Fairbanks, AK.