Testing the Effectiveness of a High Latitude Marine Reserve Network
Phase 1: Distribution of King and Tanner Crabs in Glacier Bay, Alaska

Progress Report

S. James Taggart
Jennifer Mondragon
Alexander G. Andrews
Julie K. Nielsen
L. James de la bruere

Prepared for the National Park Service, Glacier Bay National Park

USGS- Alaska Science Center
Glacier Bay Field Station
3100 National Park Road
Juneau, AK 99801

April 2003

Testing the Effectiveness of a High Latitude Marine Reserve Network
Phase 1: Distribution of King and Tanner Crabs in Glacier Bay, Alaska

Progress Report

S. James Taggart*	(907) 364-1577	jim_taggart@usgs. gov
Jennifer Mondragon*	(907) 364-1579	jennifer_mondragon@usgs. gov
Alexander G. Andrews*	(907) 364-1568	alex_andrews@usgs. gov
Julie K. Nielsen*	(907) 364-1578	julie_nielsen@usgs. gov
L. James de la bruere	(907) 697-2652	jim_de_la_bruere

*US Geological Survey, 3100 National Park Road, Juneau, Alaska, 99801
**US Geological Survey, PO Box 140, Glacier Bay National Park, Gustavus, Alaska 99826

Prepared for the National Park Service, Glacier Bay National Park

USGS- Alaska Science Center
Glacier Bay Field Station
3100 National Park Road
Juneau, AK 99801

April 2003

INTRODUCTION

During the 1990's, declining fish and invertebrate stocks around the world caused doubt about the long-term sustainability of many fisheries (Ludwig et al. 1993, Rosenberg et al. 1993, National Research Council 1995, Agardy 1997, Hastings and Botsford 1999, Murray et al. 1999). Alaskan crustacean fisheries are particularly prone to serial depletion and collapse (Orensanz et al. 1998). In response to fisheries crashes, an emerging theoretical and empirical body of information hypothesizes that "no-take marine reserves" may promote marine biodiversity, increase scientific understanding, and enhance the long-term sustainability of many fisheries (Plan Development Team 1990, Carr and Reed 1993, Rowley 1994, Agardy 1995, Ticco 1995, Bohnsack and Ault 1996, Allison et al. 1998, Coleman and Travis 1998, Lauck et al. 1998, Garcia-Charton and Perez-Ruzafa 1999, Murray et al. 1999, Ward et al. 1999, National Research Council 2000). Most of the marine reserve effects, however, have been demonstrated in tropical areas (Agardy 2000); data on the effectiveness of marine reserves are limited from high latitude ecosystems (Rogers-Bennett et al. 1995, Murawski et al. 2000, Paddack and Estes 2000).

In 1999, the US Congress created one of North America's largest temperate marine reserves by closing commercial fishing in parts of Glacier Bay National Park, Alaska (Department of the Interior 1999). The commercial fishing closures in Glacier Bay created a network of five protected areas, which vary in shape, and range in size from 40 to 280 km^2 (Fig. 1). Since so little is known about reserves in high latitude waters and because the reserves created in Glacier Bay are potentially large enough to meet conservation objectives for many species, the opportunity in Glacier Bay to test the effectiveness of a marine reserve network as a marine conservation management tool is socially and scientifically important.

In order to be effective, a marine reserve must be large enough to protect a sufficient proportion of the population for positive effects such as increased body size, density, or fecundity to be realized (Polacheck 1990). In addition, an effective reserve must include relevant habitat for the protected species (Dugan and Davis 1993). If the goal of a reserve is to export larvae, genes, juveniles, or adults to a larger surrounding area, it needs to be located in a portion of the species' range that acts as an ecological source, rather than a sink (Pulliam 1988, Pulliam and Danielson 1991, Carr and Perry 1997, Roberts 1998, Crowder et al. 2000). Marine reserves are likely to be an effective conservation tool for organisms that have relatively sedentary adult life stages (compared to the size of the reserve) and highly mobile larval stages, so the reserve can "seed" surrounding areas (Nowlis and Roberts 1999, Chiappone and Sealey 2000, Martell et al. 2000, Murawski et al. 2000, Pitcher et al. 2000, Roberts 2000, Warner et al. 2000).

Reserve size and shape are also vital factors that influence whether a marine reserve will effectively protect adult breeding populations (Polacheck 1990, Demartini 1993, Guenette and Pitcher 1999). A small boundary to reserve area ratio can result in lower movement across the reserve boundary, and thus increase the spawner stock biomass within the reserve, and shift the age structure of the population to older individuals. The retention of breeding adults in marine reserves is quantified in simulation models as transfer rate; these models demonstrate that transfer rate is central to reserve effectiveness (Polacheck 1990, Demartini 1993, Guenette and Pitcher 1999).

The long-term goal of this project is to measure the transfer rate of Pacific halibut (*Hippoglossus stenolepis*), Tanner crab (*Chionoecetes bairdi*), and red king crab (*Paralithoides camtschaticus*), between the newly created reserves and the adjacent area remaining open to commercial fishing. A second long-term goal is to measure detailed movement patterns of crabs and halibut to identify essential fish habitat, seasonal changes in distribution, migration patterns, and changes in movement and habitat requirements with ontogeny. For the first time, advances in telemetry are making it possible to measure these population processes.

Currently, many sonic tracking systems utilize tags that broadcast at different frequencies and must be manually detected and decoded by a human observer. This means that sample sizes must be small, effort to detect and identify tags is large, and only small areas can be searched. Typically only a few transmitters can be located within a few km area without an overlap of signals and subsequent loss of data. Also, as the number of sonic transmitters being tracked increases, the aural signals become increasingly cumbersome. New tracking tools are needed for efficient tracking of large samples to be able to describe the movement characteristics of a population.

We are collaborating with Lotek Wireless Inc. (a developer and manufacturer of fish and wildlife tracking systems) to develop technologies which allow us to search large areas, detect and decode large samples of sonically tagged crabs, and quickly determine the position of those animals by computing the time differences of signal arrival at multiple hydrophones. Although the components of this system are not new, the reconfiguration of components into an integrated mobile tracking and/or positioning system will allow us to address population-level movement questions previously viewed as impossible. This is a system that will be developed over the next couple of years (pending funding).

Our long-term vision is to simultaneously measure the transfer rate of multiple species among multiple reserves and the adjacent area remaining open to commercial fishing. King crabs, Tanner crabs and halibut will be sonic-tagged within in each of these areas and their movements will be detected by submersible data loggers deployed along the reserve boundaries creating ultrasonic gates. The data loggers will record tagged animals that move across the reserve boundaries. The location of tagged animals will be periodically determined by visiting grid stations or by systematically searching with towed hydrophones. In 2002, we initiated the research by sonic-tagging king and Tanner crabs in the East Arm reserve and installing an acoustic gate near the boundary. This will provide the opportunity to further develop the tracking and ultrasonic gate technology in collaboration with Lotek Wireless.

Since our goal is to estimate the movement of crab and halibut populations, the distribution of the tags in the population is a critical experimental design consideration. The tags need to be distributed randomly in the population. Before this can be accomplished, the relative densities of the populations throughout Glacier Bay need to be estimated. In 2002 we conducted a survey of Glacier Bay to estimate the relative densities of king and Tanner crabs. In addition, the survey provided a basic inventory of the macro invertebrate resources throughout Glacier Bay and how those species are spatially distributed in a recently deglaciated fjord ecosystem.

This progress report focuses on our methods. We also present preliminary results from the relative density survey and movement data from the sonic-tagged king and Tanner crabs.

STUDY SITE

Our study sites include the central part of Glacier Bay and five adjacent areas in the Park where commercial fishing was recently closed: Geikie Inlet, Scidmore Bay-Charpentier Inlet, West Arm, East Arm and Beardslee Islands (Fig. 1). The central portion of the Bay remains open to commercial halibut and Tanner crab fishing. Thus, the five closed areas are reserves for Tanner crabs and halibut while the entire bay is a reserve for red king crabs.

It is important to clarify that sport fishing and personal use fishing are allowed in all areas of Glacier Bay including the reserves. Thus it would be incorrect to classify the reserve areas as no-take-marine-reserves. We think, however, that the amount of sport fishing in the reserve areas is small. Furthermore the reserves that are wilderness waters (Scidmore Bay-Charpentier Inlet, and Beardslee Islands) are non-motorized during the summer (May 15 – September 15). Portions of two other reserves are wilderness waters (Adams Inlet which is part of the East Arm reserve; Rendu which is part of the West Arm reserve). Two parts of the East Arm are closed to motorized vessels for six weeks during the summer (Muir Inlet Head is closed from June 1 to August 31 and Wachusett Inlet is closed from July 16 to August 31). When areas are closed to motorized vessels it limits the sport harvest to people fishing from shore or from kayaks. From a scientific point of view we think that it is currently valid to study the movement dynamics as though the reserve areas are no-take-marine-reserves. The amount of sport fishing in the reserve areas could change in the future and compromise long-term studies. If long-term studies were undertaken it would be logical to monitor the level of sport harvest.

METHODS AND RESULTS

Methods: Research Objective 1

1.a Estimate the relative densities of crabs in the reserves and in the central Bay.

1.b Estimate the size frequency distribution of crabs in the reserves and in the central Bay.

The reserves are composed of protected fjords and bays while the open portion of the bay is less enclosed. The reserve areas, except the Beardslee Islands, are heavily influenced by glacial inputs compared to the central Bay. The Beardslee Islands area network of islands characterized by relatively shallow water. Thus, there are large differences in the type of habitat contained in the reserves and the open area. Consequently, we expect differences in relative density between the reserves and the open area.

The relative abundance of crabs was estimated within the study area in July/August, 2002. Crabs were collected with conical, top-loading 7.3 ft X 3 ft commercial Tanner crab pots which have the same specifications as pots used by the ADF&G for king and Tanner crab surveys. We used the same methods (soak time, bait type, bait quantity) as ADF&G (Clark et al. 1999), since standardized methods will facilitate interagency analyses of the pooled data. As the pots were retrieved, we counted and identified all organisms to species (rarely to genus). To sample juvenile crabs, a commercial shrimp pot was attached to the conical Tanner crab pot with a 20 m tether. We recorded the sex, carapace size, shell condition, appendage damage, and noticeable disease for each crab. Carapaces were measured to the nearest mm with vernier calipers. Tanner crab carapace widths were measured and king crab carapace lengths were measured. Shell conditions were categorized as soft, new, old or skip molt (Jadamec et al. 1999). We examined the appendages and recorded missing or regenerating appendages.

Crab pots were set according to a systematic sampling design (Fig. 1). Based on power analyses, our goal was to sample a minimum of 200 stations inside the reserves and 200 stations in the open area. Since the area remaining open to Tanner and halibut fishing is slightly larger than the reserve area, the pots were spaced 1.5 and 1.8 km respectively. We divided the stations into clusters of 16 pots (the number of pots we sampled each day) and ordered the sampling of the clusters so that sampling effort was distributed from the head to the mouth of Glacier Bay during each sampling trip (3 eleven day trips). The only stations we did not sample were areas hazardous to navigation (Johns Hopkins Inlet, Adams inlet and a few stations in the Beardslee Islands). The pots were set in the afternoon and retrieved the morning of the following day. Our sampling design required us to sample all locations independent of depth. Since much of Glacier Bay is deep, many days we set and retrieved 8 km of buoy line; managing the buoy line was a significant logistical obstacle. Commercial Tanner crab vessels coil the buoy line into 25 or 50 fathom sections. Instead we flaked ½ inch “soft lay” line, manufactured by Everson Rope Inc., into tubs, which eliminated the fatigue associated with coiling the buoy line.

Research Vessel

A 50’ USGS research vessel, R/V Alaskan Gyre, was used to deploy and retrieve crab pots. The location of the vessel was continuously recorded by downloading Global Positioning System (GPS) fixes and times onto a computer.

Data Analysis: Relative Density

Density is assumed to be proportional to catch-per-unit-effort (CPUE) (Quinn II and Deriso 1999). Thus, the relative density in the reserves and in the open area can be estimated from the CPUE. To look for broad spatial patterns we plotted the relative densities of Tanner crabs and King crabs on GIS maps. Female Tanner crabs molt to maturity with a terminal molt, which is morphologically distinct from juveniles. Consequently it was easy to split female Tanner crabs into juveniles and adults. We classified males as (small< 80mm) and large ($\geq$ 80mm). We also classified males > 140 mm as commercially legal. We plotted the distribution of large males, adult females, small males, juvenile females, and legal male crabs. The density data were not normally distributed so we tested for differences in relative density of crabs in the central Bay to the reserve network (all five reserves combined) with a Mann-Whitney test. We tested for density differences among the 5 individual reserves and the central Bay with a Kruskal-Wallis test.

To determine if sex and age classes co-occurred on a small scale, we subdivided the catch at each station by sex and maturity (mature females, juvenile females, small males and large males) and plotted the age-sex classes against each other.

The total number of king crabs captured was small so we only split the sample by sex. We plotted the relative densities of king crabs (males and females) on a GIS map. We tested for differences in relative densities of king crabs in the central Bay to the reserve network (all five reserves combined) with Mann-Whitney test. We tested for density differences among the 5 reserves and the central Bay with a Kruskal-Wallis test.

Data Analysis: Size Frequency

We compared the size frequency of central Bay to the reserve network (all reserves combined) by plotting size frequency histograms. We also compared the size frequency among the individual reserves and the central Bay. We split the Tanner crab size frequency analyses by sex and age class. Since female Tanner crabs molt to maturity with a terminal molt, we tested to see if there were differences in the size of adult females.

For king crabs, we compared the size frequency of males and females. There were too few king crabs captured in most of the reserves to compare the size frequencies between the central Bay and the reserve network or among the individual reserves and the central Bay.

Results: Research Objective 1

Tanner crabs are widely distributed in Glacier Bay. Sixty-nine percent of the pots captured at least one Tanner crab. The only large area where crabs were absent was the lower Bay south of the north end of Willoughby Island, excluding the Beardslee Islands and Bartlett Cove (Fig. 2a, Fig. 3a, and Fig. 4a). The adjacent area to the north was characterized by a high density of adult Tanner crabs (Fig. 2a), suggesting the density changes abruptly.

In contrast to Tanner crabs, red king crabs were captured in only 7% of the pots. The king crabs were extremely aggregated; 73% of the king crabs were captured in 7 pots near the mouth of Adams Inlet (East Arm reserve) (Fig. 5a). The densities of king crabs were not significantly different between the reserve network and the central Bay or among the individual reserves and the central Bay. The variance among pots was very high and consequently the power for detecting differences was very poor.

When we tested for differences in relative densities of Tanner crabs between the reserve network and the open central Bay, we found no significant differences in densities of large males (Fig. 2b), small males (Fig. 3b), juvenile females (Fig. 3c), or legal males (Fig 4b). There was a significantly higher density of adult females in the reserve networks than in the central Bay (Fig. 2c).

The densities of crabs were significantly different among the individual reserves and the central Bay for large males (Fig. 2d), adult females (Fig. 2e), juvenile females (Fig. 3e), and legal males (Fig. 4c). Small males were not significantly different. The significant differences have not been tested with a multiple range test to see which reserve pairs are different.

From the distribution maps it is clear that there are areas of high abundance for specific age and sex classes. Large males and adult females were abundant in a number of locations but the most extensive area of high concentration extended from the mouth of Adams Inlet to the Marble Islands (Fig. 2a). Wachusett Inlet, the northern portion of Scidmore Bay, the southern portion of Charpentier Inlet, the shelf around North Marble Island and southeastern portion of Bartlett Cove were important juvenile areas (Fig 3a).

Visual inspection of age class-sex scatter plots suggests that juvenile females and small males were more likely to co-occur (Fig. 6c) and old shell adult females and large males were more likely to co-occur (Fig. 6i). Old Shell adult females and large males tend not to occur with juvenile females and small males (Fig. 6b, 6d, 6h, 6j). New shell adult females did show a weak pattern of co-occurrence with the other sex-size classes.

We compared the size frequency distributions of Tanner crabs of each sex and age class in the reserve network to the corresponding sex and age class in the central Bay. The size frequency of males, adult females, and juvenile females was similar between the reserve network and the central Bay (Fig. 7).

We compared the size frequency among the individual reserves and the central Bay. Scidmore-Charpentier reserve had a bimodal size distribution for male Tanner crabs (Fig. 8j). The large crabs in this reserve represented some of the largest crabs captured in Glacier Bay (Fig. 8j). Geikie contained few small crabs (females or males) (Fig. 8c and Fig. 8i). There were significant differences in the mean size of adult females (Fig. 9) among the reserves. The largest adult females occurred in Geikie and the smallest occurred in the East Arm.

Since we caught the majority of the king crabs in the East Arm we pooled all of the king crab data for the size frequency analysis. Male king crabs were larger than female king crabs (Fig. 10).

Methods: Research Objective 2

2. Estimate the length of time king and Tanner crabs remain in the East Arm reserve.

Acoustic Telemetry System

Acoustic telemetry requires the use of ultrasonic transmitters that emit a signal at a defined burst interval and frequency, hydrophones to “listen” for the signal, and a receiver to decode the signal.

Sonic Tags

Crabs were tagged with ultrasonic transmitters manufactured by Lotek Wireless Inc. Lotek transmitters incorporate advanced code division multiple access (CDMA) technology that makes it possible for small tags to have a long operational life and short burst interval. This allows for efficient tracking and more precise positioning. King crabs (male and female) and male Tanner crabs were tagged with MAP16_2 sonic tags, which are cylindrical and measure 16 mm in diameter by 88 mm long. The tags have a burst interval of 20 seconds and transmit at 77 kHz. The expected operational life is 3 years. Tags have activity sensors to determine if the transmitter is still on a “live” crab (i.e., determine if the crab molted or died). Because female Tanner crabs are small, we did not tag females and they will be tagged with smaller tags during a future phase of the study.

Hydrophones

Crabs were located using a LHP_1 (Lotek) omni-directional hydrophones. We are also testing a towed hydrophone array, which was depressed to depth with a side-scan sonar fish. During preliminary testing, we were able to tow a standard omni-directional hydrophone 10 meters below the surface at 8km/hour by trailing the hydrophone behind the side-scan sonar fish. At this speed, we were able to decode tags up to 700 meters away. We are also testing a high flow hydrophone (Marschall Acoustics), which should increase the effective tow speed markedly.

Receiver

Lotek’s MAP telemetry systems combine advanced signal processing methods with code division multiple access (CDMA) coding, similar to that found in cellular communications systems. This technology has several advantages: 1) the unique identification of tens of thousands of tags, allowing the overlap of several research efforts without limiting the number of unique codes; 2) hundreds of tags can be simultaneously detected and reliably decoded, allowing the utilization of large sample sizes; 3) data from sensor equipped transmitters can be efficiently transferred within a single detection event, so the animal’s environment can be simultaneously monitored e.g., temperature, depth, activity; 4) “coding gain” increases the number of detections for a given transmitter’s output power, background noise and receiver range versus conventional pulse position coded acoustic telemetry; and 5) because all tags transmit on the same acoustic frequency, frequency scanning is not required.

The MAP RT digitally detects and decodes (including sensor data) the signals from the sonic tags, which eliminates the need for an observer to listen for sonic tags with headphones. The dual port input capability of the receiver allows detection and processing from two independent channels which permits processing of very accurate time differences of signal arrival time which can be use for determining accurate direction-of-arrival estimates.

Data Loggers

An ultrasonic gate was constructed by mooring 4 independent submersible data loggers (Fig. 11) along the boundary of the East Arm reserve. The data loggers record the sonic tags’ individual identification and the date and time when a tagged animal comes into range.

Data loggers were suspended 20 meters from the bottom with subsurface flotation (Fig. 12). Subsurface flotation eliminates numerous problems associated with surface buoys (e.g., navigational hazard, fouling with kelp or logs, visual impact to visitors, freezing in ice during the winter). Disposable anchors were used to secure the moorings to the bottom. Marinna Martini, an ocean engineer with the USGS Woods Hole Field Center, modeled the mooring configuration (i.e., anchor, hardware, flotation, line, etc.) based on estimated current at the East Arm reserve boundary. Data loggers are retrieved by remotely activating the acoustic release (Oceano Technologies Inc).

Sonic tags were attached to a random sample of the mature portion of the populations inside the East Arm reserve. Sonic tags were attached while we conducted the relative density sampling.

Our goal is to estimate the movement of the Tanner crab population in the study area. To accomplish this objective, the tags need to be distributed randomly throughout the population. During the second sampling trip we sampled every other station in the East Arm, (the reserve where we were planning to attach the sonic tags). On the third sampling trip we distributed the sonic tags in the East Arm proportional to the relative abundance estimated from the previous sampling trip. All sonic tagged animals were released at the location where they were captured.

To minimize the loss of sonic tags by molting we tagged male Tanner crabs that had recently molted and were greater than 125 mm (Table 1); these crabs should have a molt interval greater than two years (Paul and Paul 1995). Recently molted male crabs, were identified by carapace condition (Jadamec et al. 1999). To minimize tag loss from molting we selected recently molted king crabs with a carapace length greater than 140 mm (Table 1). The sonic tags were glued to the carapace with fast cure epoxy resin (Stone et al. 1992) (epoxy: *BioFix 911*, Progressive Epoxy Polymers, Inc) and fiberglass tape (methods developed by authors) (Fig. 13).

Sonic tags were relocated in November 2002 and February 2003. During November we located the sonic tags by suspending a hydrophone in the water at stations 1.5 km apart. To increase the accuracy of the crab locations, in February, we reduced the distance between survey stations to .75 km.

Results: Research Objective 2

Although we have only relocated the sonic-tagged crabs twice (November and February) there are marked differences between the Tanner and king crab movements. King crabs moved greater distances than the Tanner crabs (Fig. 14). The Tanner crabs appear to move independently of each other (Fig. 15). In contrast, the majority of the king crabs moved from their release locations to subsequent locations as a unit (Fig. 16).

REFERENCES

Agardy, T., editor. 1995. The science of conservation in the coastal zone: new insights on how to design, implement and monitor marine protected areas. IUCN, Gland, Switzerland.

Agardy, T. 2000. Information needs for marine protected areas: scientific and societal. Bulletin of Marine Science **66**:875-888.

Agardy, T. S. 1997. Marine protected areas and ocean conservation. R.G. Landes Company.

Allison, G. W., J. Lubchenco, and M. H. Carr. 1998. Marine reserves are necessary but not sufficient for marine conservation. Ecological Applications **8**:S79-S92.

Bohnsack, J. A., and J. S. Ault. 1996. Management strategies to conserve marine biodiversity. Oceanography **9**:73-82.

Carr, M. H., and D. C. Reed. 1993. Conceptual issues relevant to marine harvest refuges: examples from temperate reef fishes. Canadian Journal of Fisheries and Aquatic Sciences **50**:2019-2028.

Carr, S. M., and E. A. Perry. 1997. Intra- and interfamilial systematic relationships of phocid seals as indicated by mitochondrial DNA sequences. Pages 277-290 *in* A. E. Dizon, S. J. Chivers, and W. F. Perrin, editors. Molecular Genetics of Marine Mammals. Society for Marine Mammalogy.

Chiappone, M., and K. M. S. Sealey. 2000. Marine reserve design criteria and measures of success: lessons learned from the Exuma Cays Land and Sea Park, Bahamas. Bulletin of Marine Science **66**:691-705.

Clark, J., C. Botelho, D. Woodby, and G. Bishop. 1999. Project Operational Plan: Tanner Crab Population Estimation in Southeast Alaska. Regional Information Report No. 1J99-31, Alaska Department of Fish and Game.

Coleman, F., and J. Travis, editors. 1998. Proceedings fo the second William R. and Lenore Mote International Symposium in Fisheries Ecology. Allen Press, Inc, Sarasota, Florida.

Crowder, L. B., S. J. Lyman, and J. Priddy. 2000. Source-sink population dynamics and the problem of siting marine reserves. Bulletin of Marine Science **66**:799-820.

Demartini, E. E. 1993. Modeling the potential of fishery reserves for managing Pacific coral reef fishes. Fishery Bulletin **91**:414-427.

Department of the Interior. 1999. Glacier Bay National Park, AK; Commercial Fishing Regulations Final Rule. Federal Register **64**:56455-56464.

Dugan, J. E., and G. E. Davis. 1993. Applications of marine refugia to coastal fisheries management. Canadian Journal of Fisheries and Aquatic Sciences **50**:2029-2042.

Garcia-Charton, J. A., and A. Perez-Ruzafa. 1999. Ecological heterogeneity and the evaluation of the effects of marine reserves. Fisheries Research **42**:1-20.

Guenette, S., and T. J. Pitcher. 1999. An age-structured model showing the benefits of marine reserves in controlling overexploitation. Fisheries Research (Amsterdam) **39**:295-303.

Hastings, A., and L. W. Botsford. 1999. Equivalence in yield from marine reserves and traditional fisheries management. Science **284**:1537-1538.

Jadamec, L. S., W. E. Donaldson, and P. Cullenberg. 1999. Biological field techniques for Chionoecetes crabs. University of Alaska Sea Grant College Program, Fairbanks.

Lauck, T., C. W. Clark, M. Mangel, and G. R. Munro. 1998. Implementing the precautionary principle in fisheries management through marine reserves. Ecological Applications **8**:S72-S78.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science **260**:17-36.

Martell, S. J. D., C. J. Walters, and S. S. Wallace. 2000. The use of marine protected areas for conservation of lingcod (*Ophiodon elongatus*). Bulletin of Marine Science **66**:729-743.

Murawski, S. A., R. Brown, and L. Hendrickson. 2000. Large-scale closed areas as a fishery-management tool in temperate marine systems: the Georges Bank experience. Bulletin of Marine Science **66**:775-798.

Murray, S. N., R. F. Ambrose, J. A. Bohnsack, L. W. Botsford, M. H. Carr, G. E. Davis, P. K. Dayton, D. Gotshall, D. R. Gunderson, M. A. Hixon, J. Lubchenco, M. Mangel, A. MacCall, D. A. McArdle, and et al. 1999. No-take Reserve Networks: Sustaining Fishery Populations and Marine Ecosystems. Fisheries **24**:11-25.

National Research Council. 1995. Understanding marine biodiversity. National Academy Press, Washington, D.C.

National Research Council. 2000. Marine Protected Areas: Tools for Sustaining Ocean Ecosystem. National Academy Press, Washington D.C.

Nowlis, J. S., and C. M. Roberts. 1999. Fisheries benefits and optimal design of marine reserves. Fishery Bulletin **97**:604-616.

Orensanz, J. M., J. Armstrong, D. A. 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. Reviews in Fish Biology and Fisheries **8**:117-176.

Paddack, M. J., and J. A. Estes. 2000. Kelp forest fish populations in marine reserves and adjacent exploited areas of central California. Ecological Applications **10**:855-870.

Paul, A. J., and J. M. Paul. 1995. Molting of functionally mature male *Chionoecetes bairdi* Rathbun (Decapoda: Majidae) and changes in carapace and chela measurements. Journal of Crustacean Biology **15**:686-692.

Pitcher, T. J., R. Watson, and A. Leung. 2000. Marine reserves and the restoration of fisheries and marine ecosystems in the South China Sea. Bulletin of Marine Science **66**:543-566.

Plan Development Team. 1990. The potential of marine fishery reserves for reef fish management in the US Southern Atlantic. NOAA Technical Memorandum NMFS-SEFC-261, NOAA Technical Memorandum NMFS-SEFC-261.

Polacheck, T. 1990. Year round closed areas as a management tool. Natural Resource Modeling **4**:327-354.

Pulliam, H. R. 1988. Sources, sinks, and population regulation. American Naturalist **132**:652-661.

Pulliam, H. R., and B. J. Danielson. 1991. Sources, sinks and habitat selection: A landscape perspective on population dynamics. American Naturalist **137**:S50-S66.

Quinn II, T. J., and R. B. Deriso. 1999. Quantative fish dynamics. Oxford University Press, New York.

Roberts, C. M. 1998. Sources, sinks, and the design of marine reserve networks. Fisheries **23**:16-19.

Roberts, C. M. 2000. Selecting marine reserve locations: optimality versus opportunism. Bulletin of Marine Science **66**:581-592.

Rogers-Bennett, L., W. A. Bennett, H. C. Fastenau, and C. M. Dewees. 1995. Spatial variation in red sea urchin reproduction and morphology: Implications for harvest refugia. Ecological Applications **5**:1171-1180.

Rosenberg, A. A., M. J. Fogarty, M. P. Sissenwine, J. R. Beddington, and J. G. Shepherd. 1993. Achieving sustainable use of renewable resources. Science **262**:828-829.

Rowley, R. J. 1994. Marine reserves in fisheries management. Aquatic Conservation: Marine and Freshwater Ecosystems **4**:233-254.

Stone, R. P., C. E. O'Clair, and T. C. Shirley. 1992. Seasonal migration and distribution of female red king crabs in a southeast Alaskan estuary. Journal of Crustacean Biology **12(4)**:546-560.

Ticco, P. C. 1995. The use of marine protected areas to preserve and enhance marine biological diversity: A case study. Coastal management **23**:309-314.

Ward, T. J., M. A. Vanderklift, A. O. Nicholls, and R. A. Kenchington. 1999. Selecting marine reserves using habitats and species assemblages as surrogates for biological diversity. Ecological Applications **9**:691-698.

Warner, R. R., S. E. Swearer, and J. E. Caselle. 2000. Larval accumulation and retention: implications for the design of marine reserves and essential habitat. Bulletin of Marine Science **66**:821-830.

Table 1. Summary of the sonic tags attached to Tanner and king crab in the East Arm in September, 2002.

Red King crab			
DateTagged	Pot Number	Sex	Carapace Length (mm)
01-Sep-02	803	Female	146
01-Sep-02	801	Male	152
01-Sep-02	801	Male	157
01-Sep-02	801	Female	158
01-Sep-02	803	Male	173
01-Sep-02	801	Male	181
02-Sep-02	KP1	Female	145
02-Sep-02	KP1	Male	150
02-Sep-02	KP3	Male	160
02-Sep-02	KP3	Female	161
02-Sep-02	KP3	Male	166
02-Sep-02	KP2	Male	171
03-Sep-02	KP8	Female	143
03-Sep-02	KP6	Female	150
03-Sep-02	KP6	Female	151
03-Sep-02	KP8	Female	154

Tanner crab			
DateTagged	Pot Number	Sex	Carapace Width (mm)
31-Aug-02	783	Male	139
31-Aug-02	785	Male	143
31-Aug-02	767	Male	145
31-Aug-02	791	Male	159
01-Sep-02	803	Male	125
01-Sep-02	805	Male	132
01-Sep-02	801	Male	140
01-Sep-02	803	Male	154
02-Sep-02	819	Male	128
02-Sep-02	823	Male	130
02-Sep-02	823	Male	131
02-Sep-02	KP1	Male	132
02-Sep-02	821	Male	134
02-Sep-02	819	Male	136
02-Sep-02	KP2	Male	141
02-Sep-02	KP1	Male	142
02-Sep-02	819	Male	151
02-Sep-02	KP1	Male	159
02-Sep-02	KP1	Male	160
02-Sep-02	KP2	Male	160
03-Sep-02	KP5	Male	151

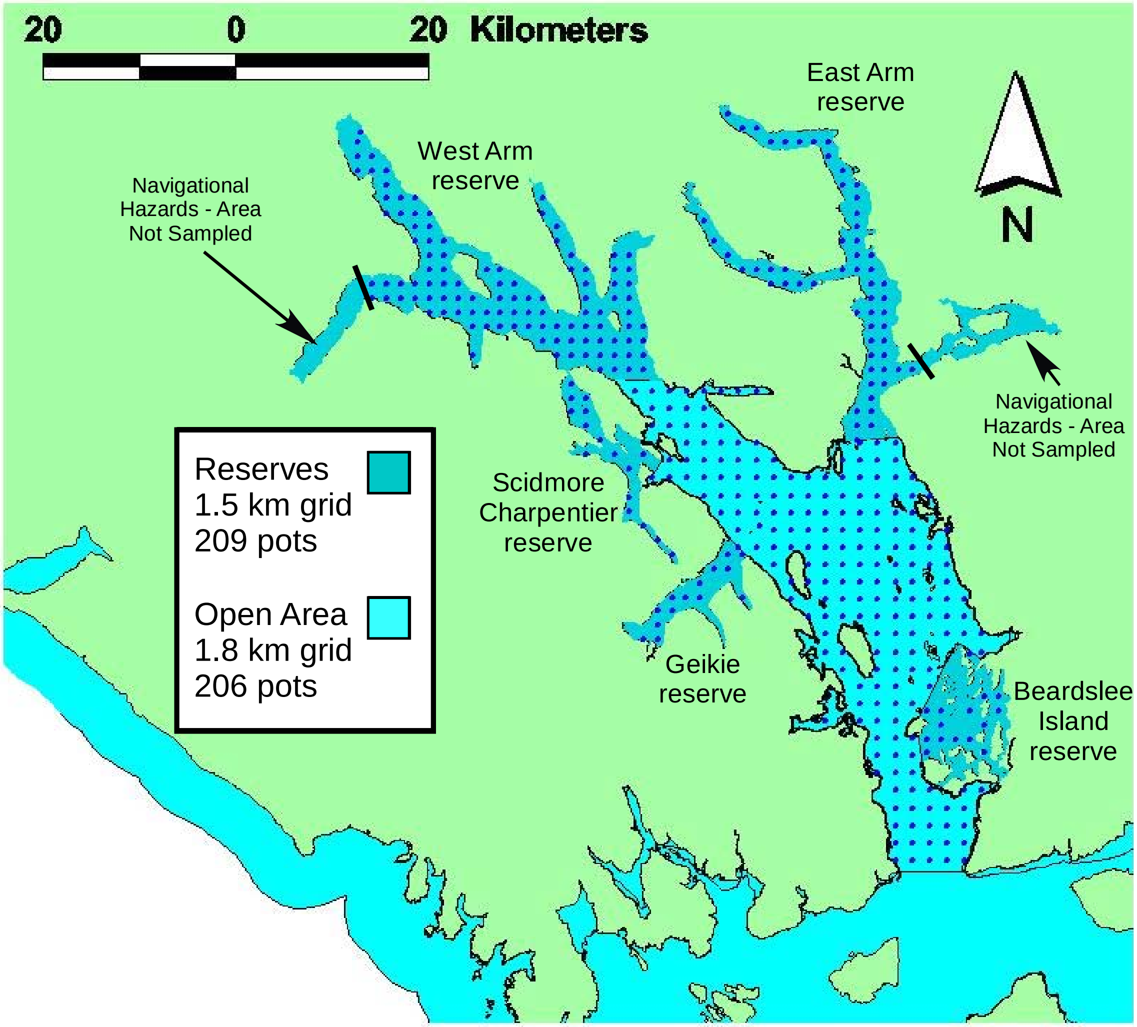


Figure 1. Systematic sampling grid for pot sampling conducted in Glacier Bay during July and Aug, 2002.

Figure 2. Distribution and Relative Abundance of Adult Tanner Crabs

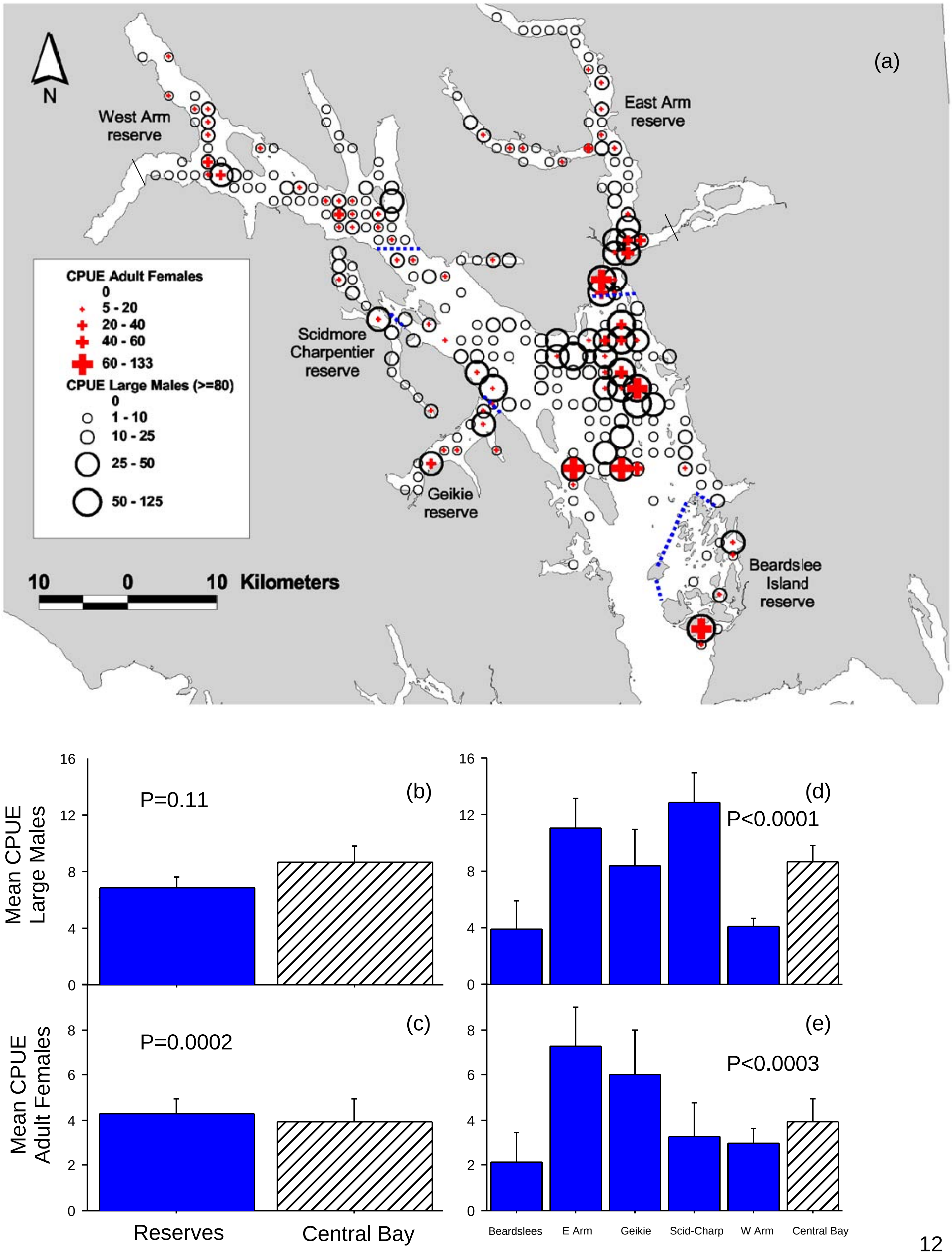


Figure 3. Distribution and Relative Abundance of Juvenile Tanner Crabs

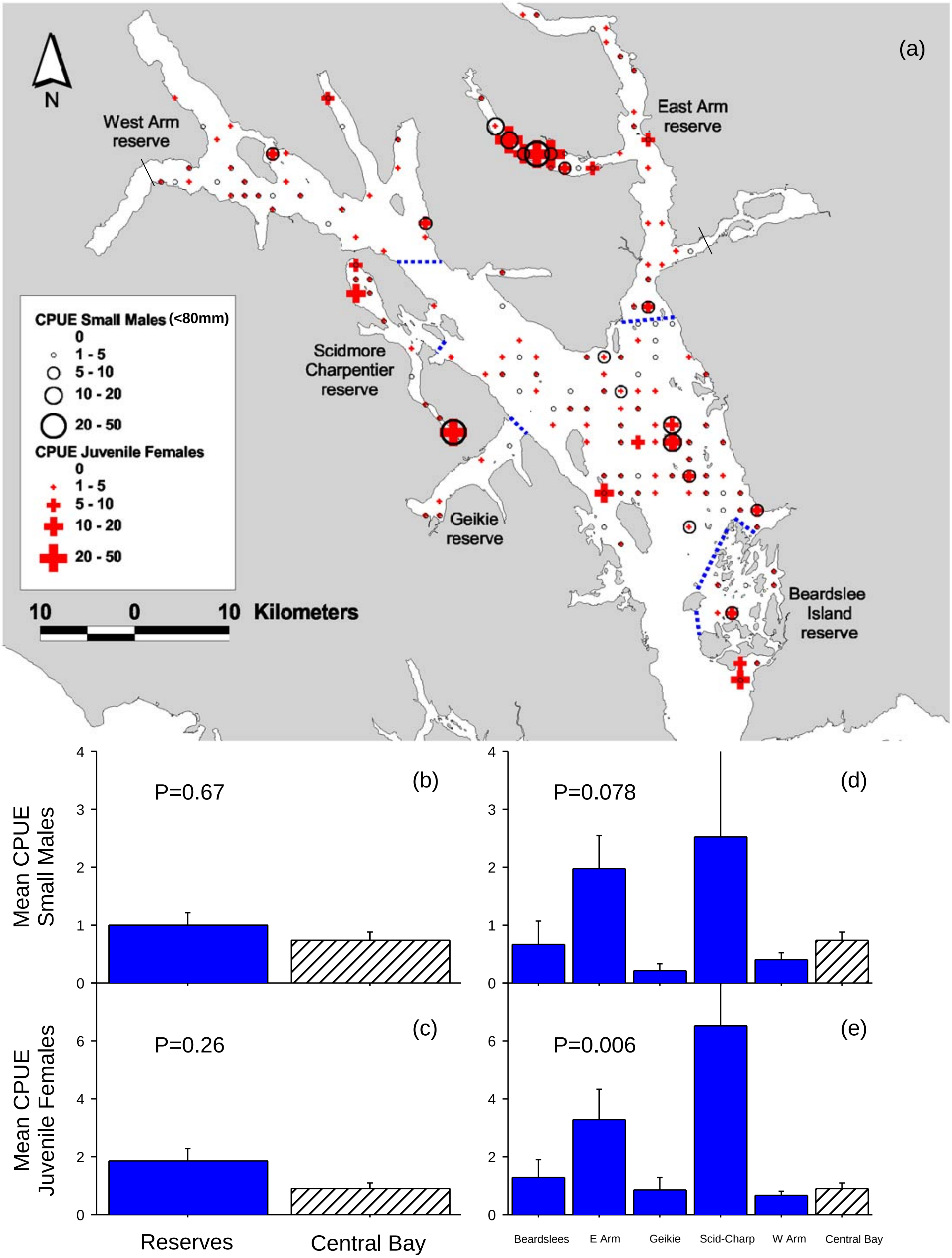


Figure 4. Distribution and Relative Abundance of Commercially Legal Male Tanner Crabs

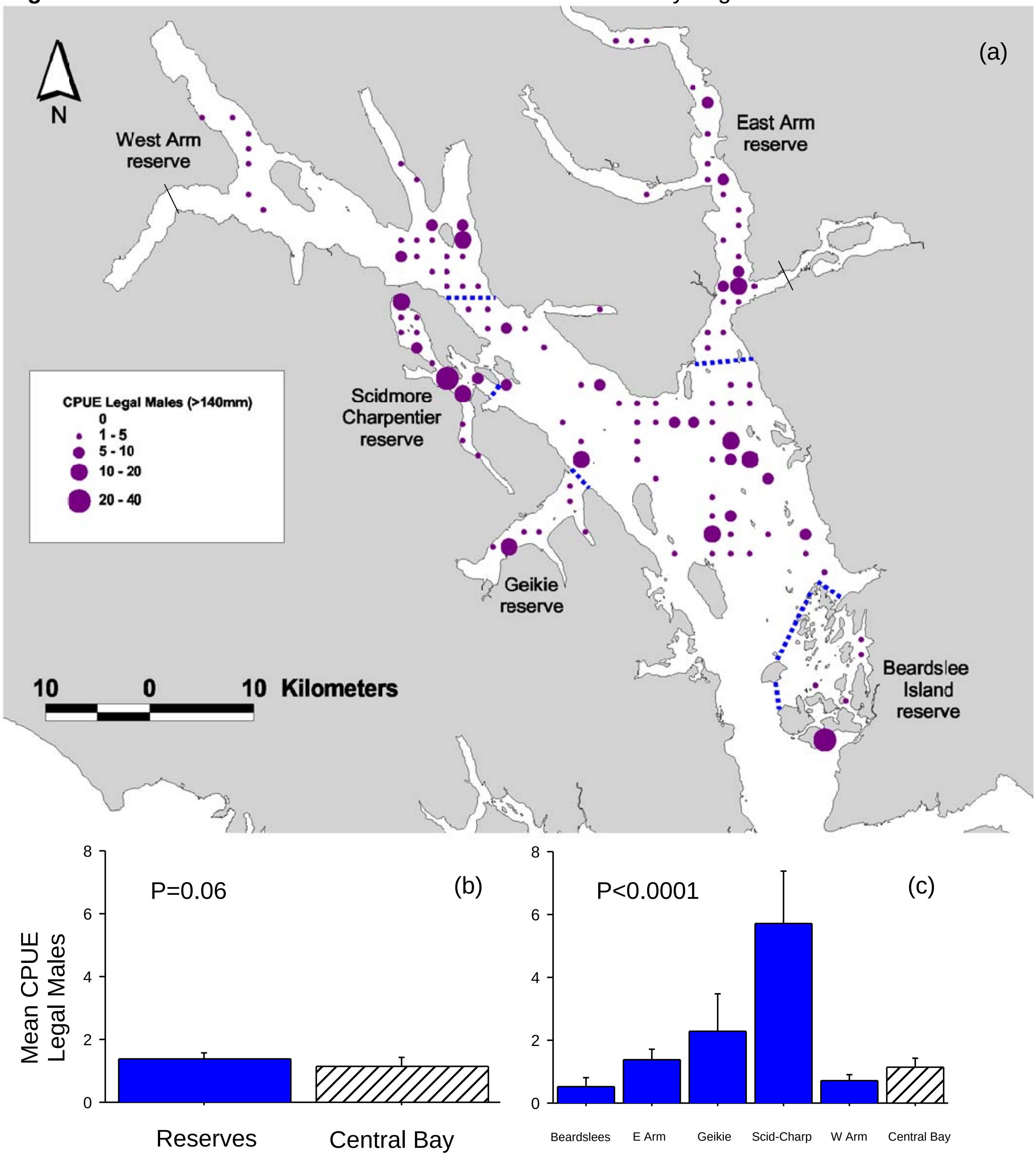


Figure 5. Distribution and Relative Abundance of Male and Female Red King Crabs

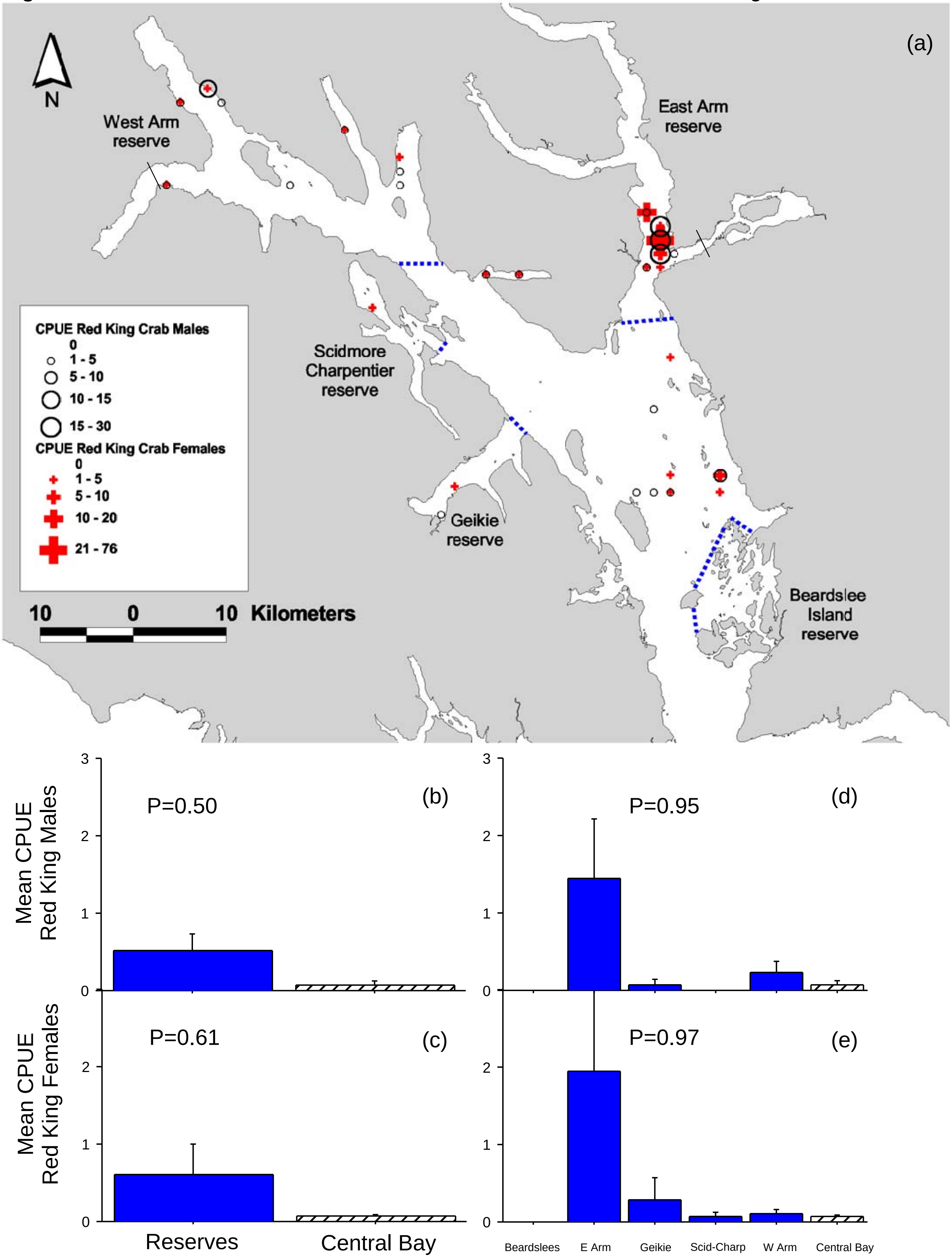
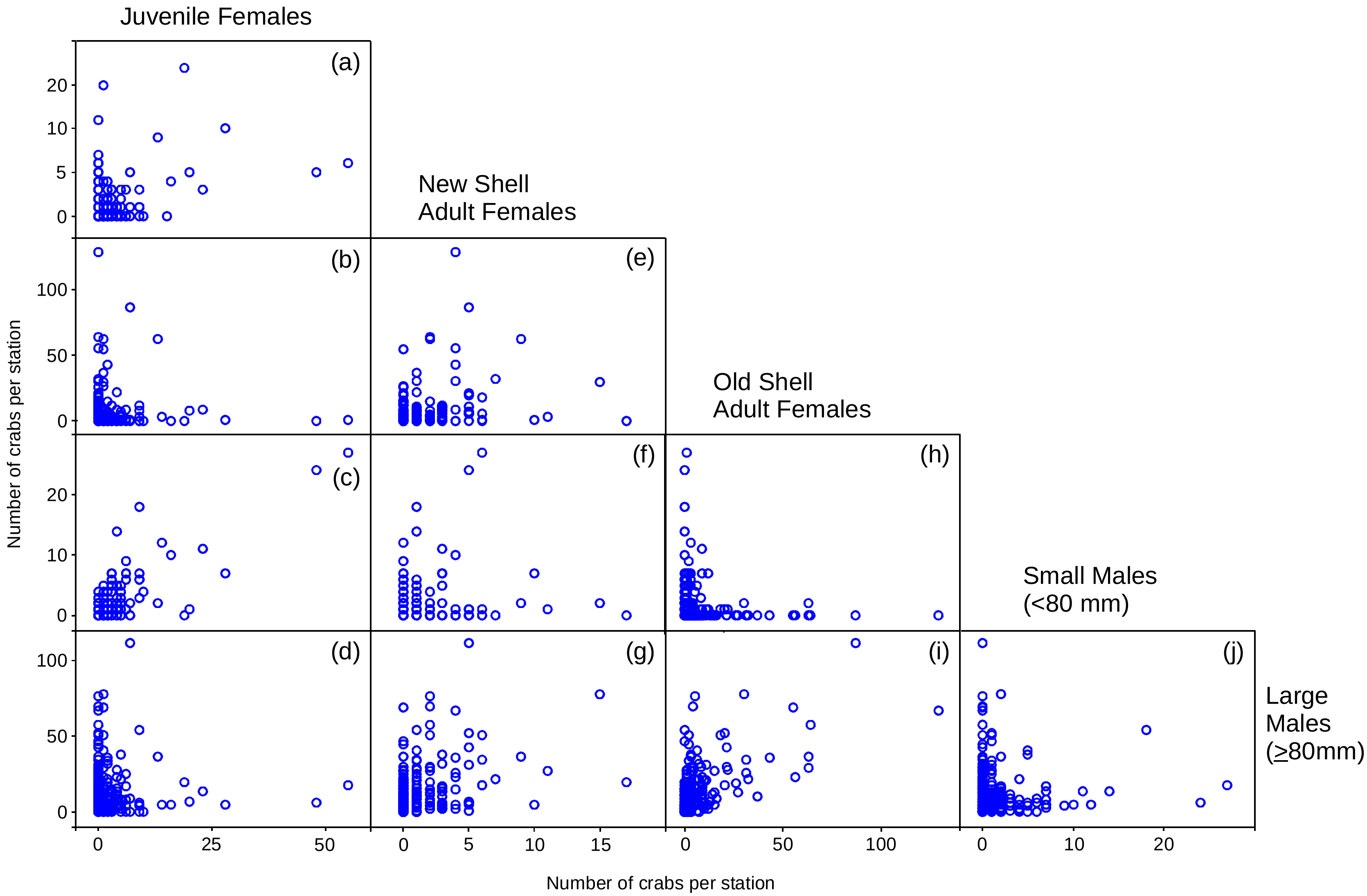


Figure 6. Occurrence of crabs at each sampling station



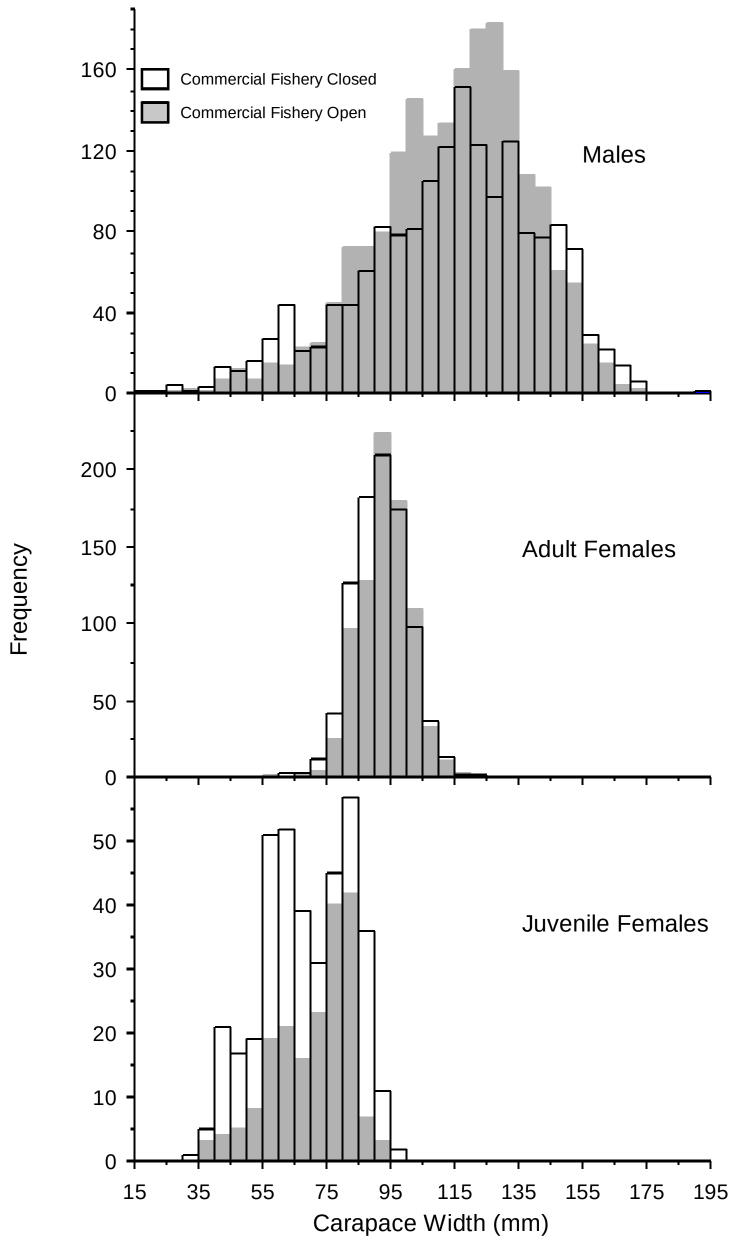


Figure 7. Size Frequency Distribution of Tanner Crabs: Comparison of Reserve Network & Area Remaining Open to Commercial Fishing

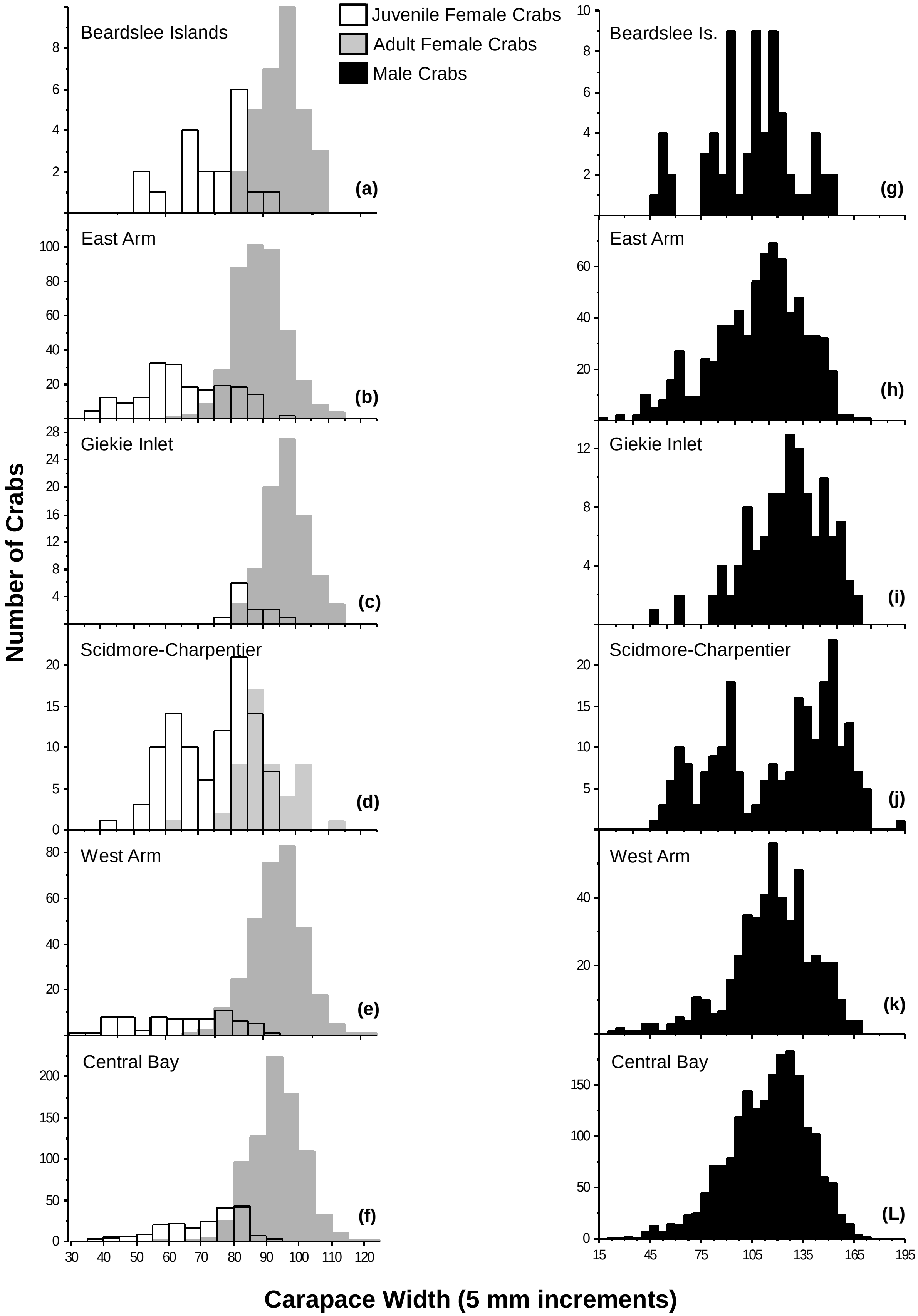


Figure 8. Size frequency distribution for Tanner crabs in individual reserves and Central Bay.

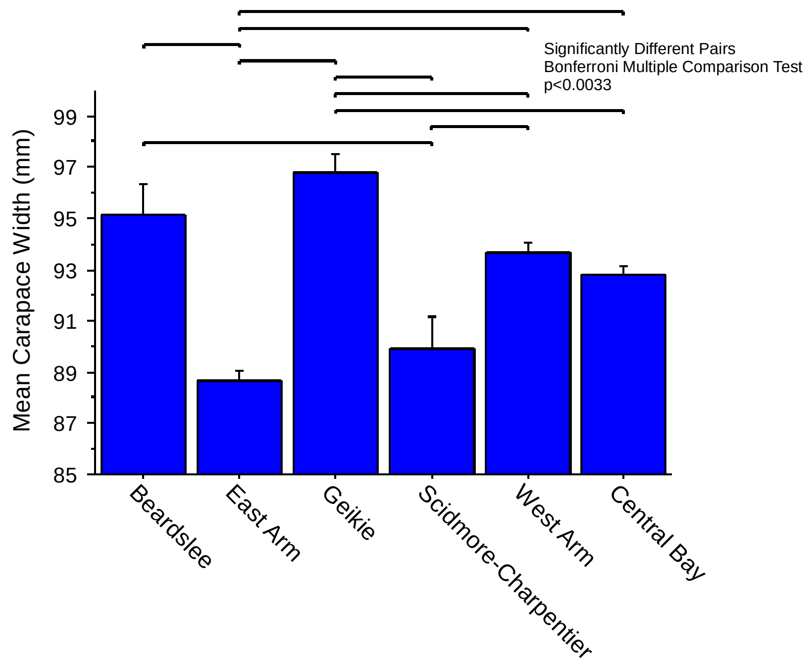


Figure 9. Mean size of adult female Tanner crabs in individual reserves and the Central Bay.

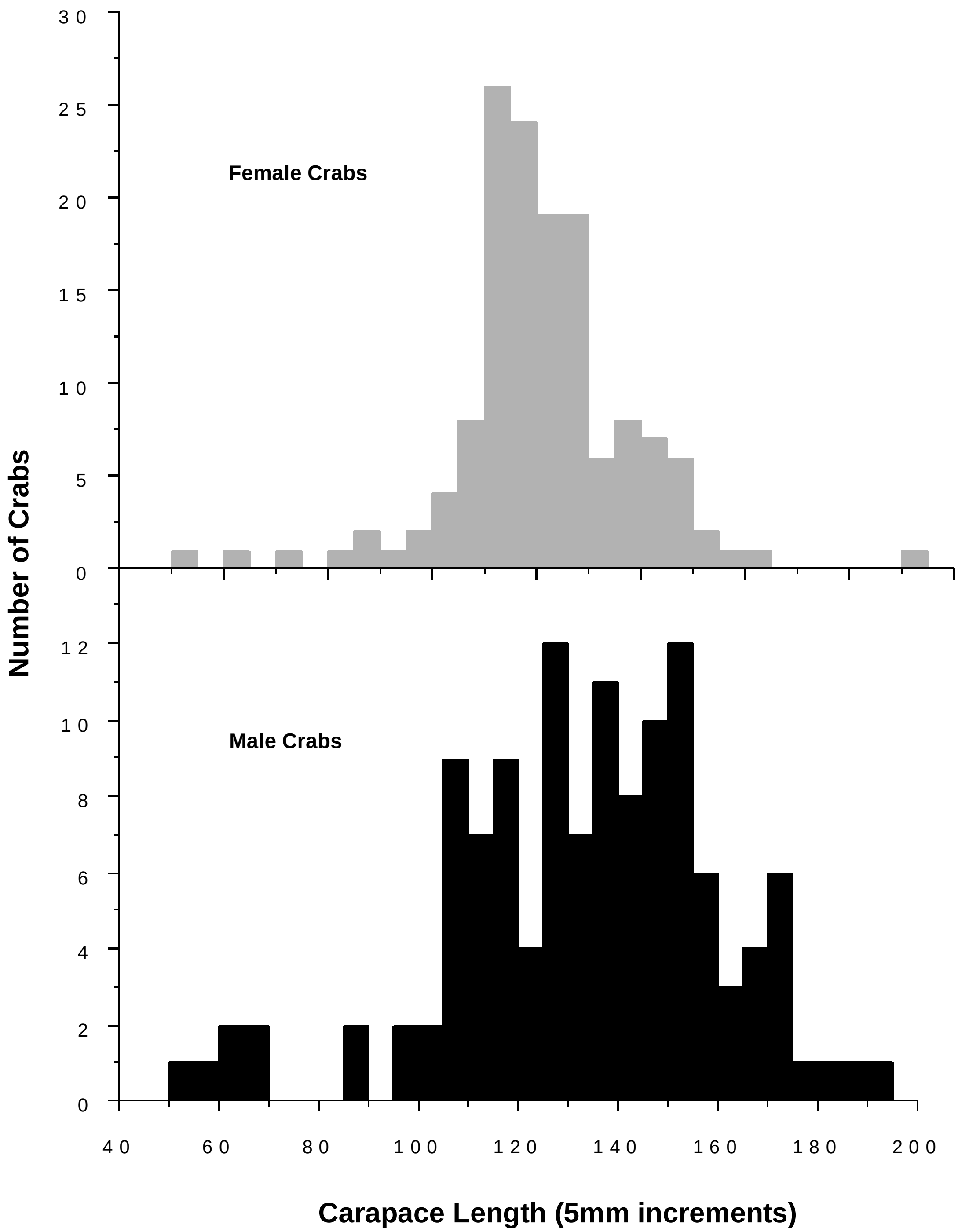


Figure 10. Size frequency distribution for red king crab in Glacier Bay.

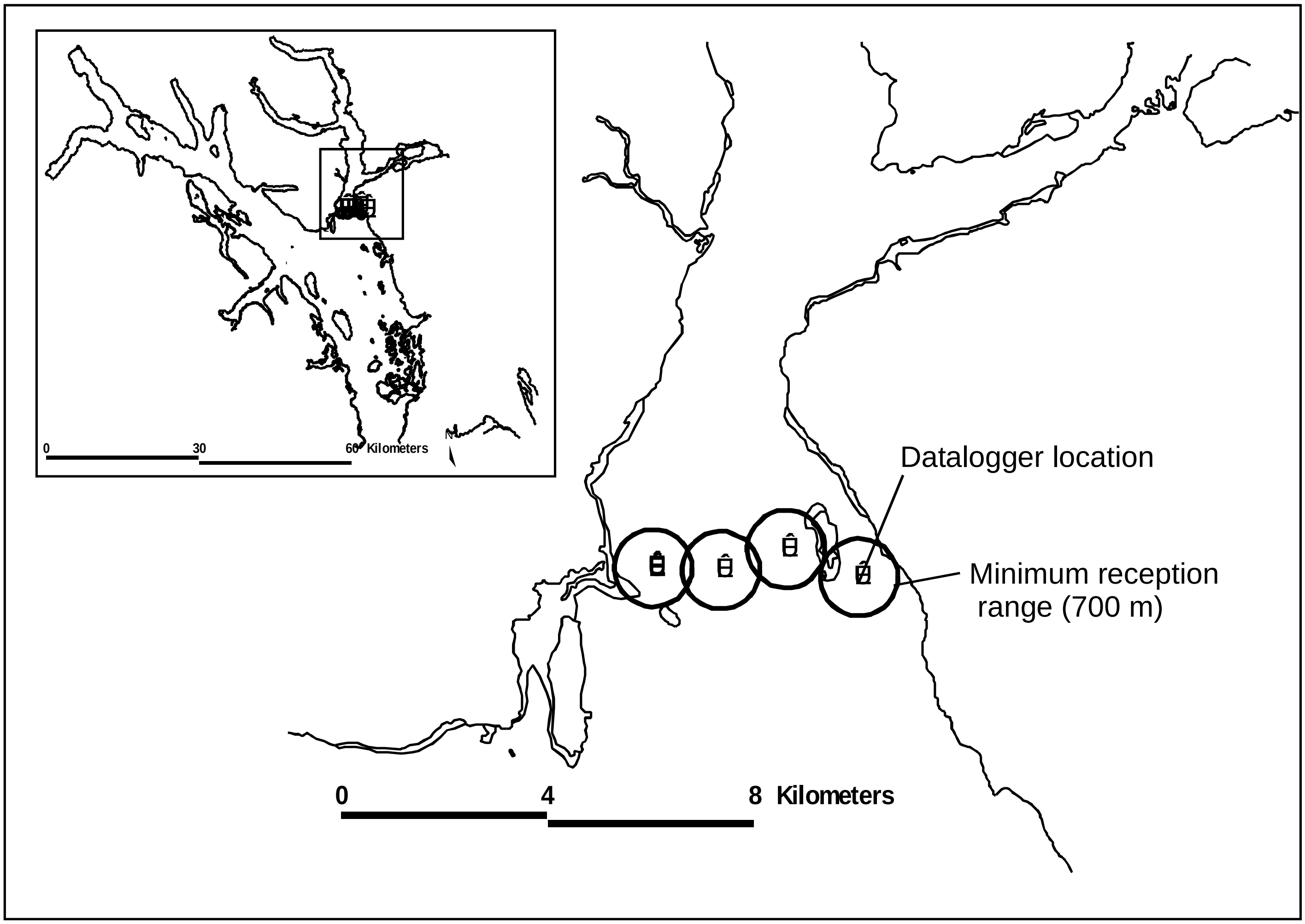


Figure 11. Datalogger locations at the entrance of the East Arm of Glacier Bay.

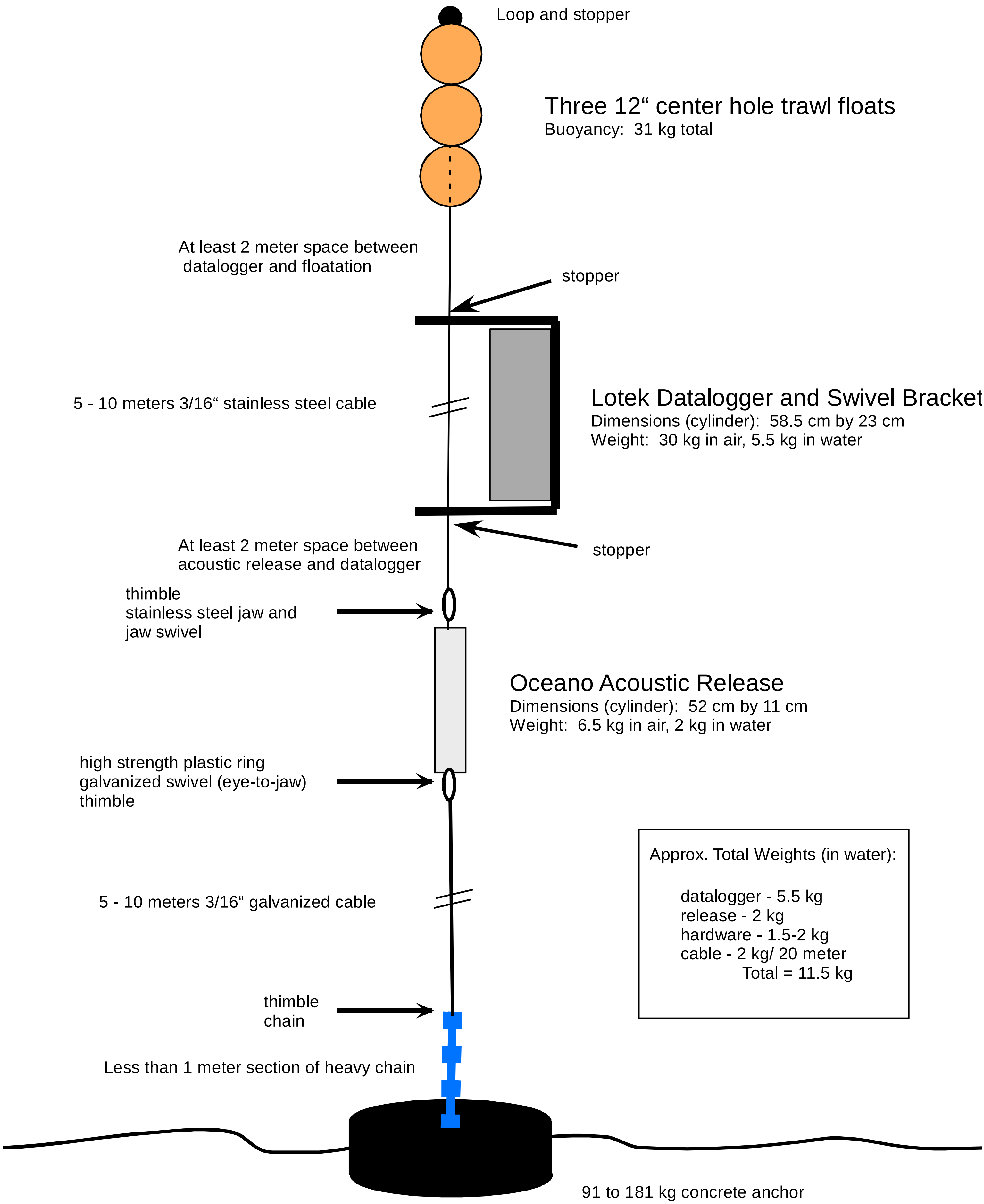


Figure 12. Mooring configuration for the submersible data loggers.

Figure 13. Male Tanner crab with sonic transmitter attached to carapace.

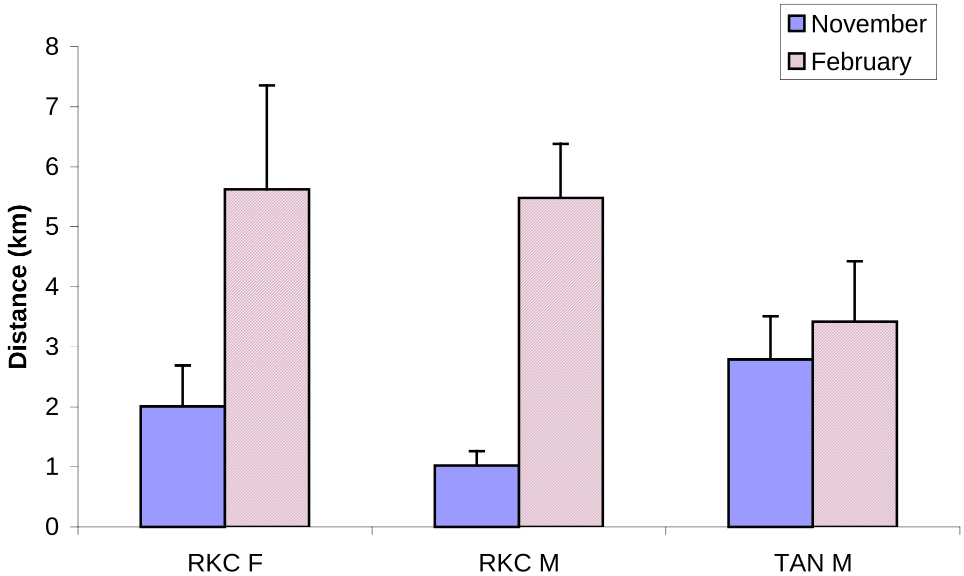


Figure 14. Average minimum distance moved from point of release.

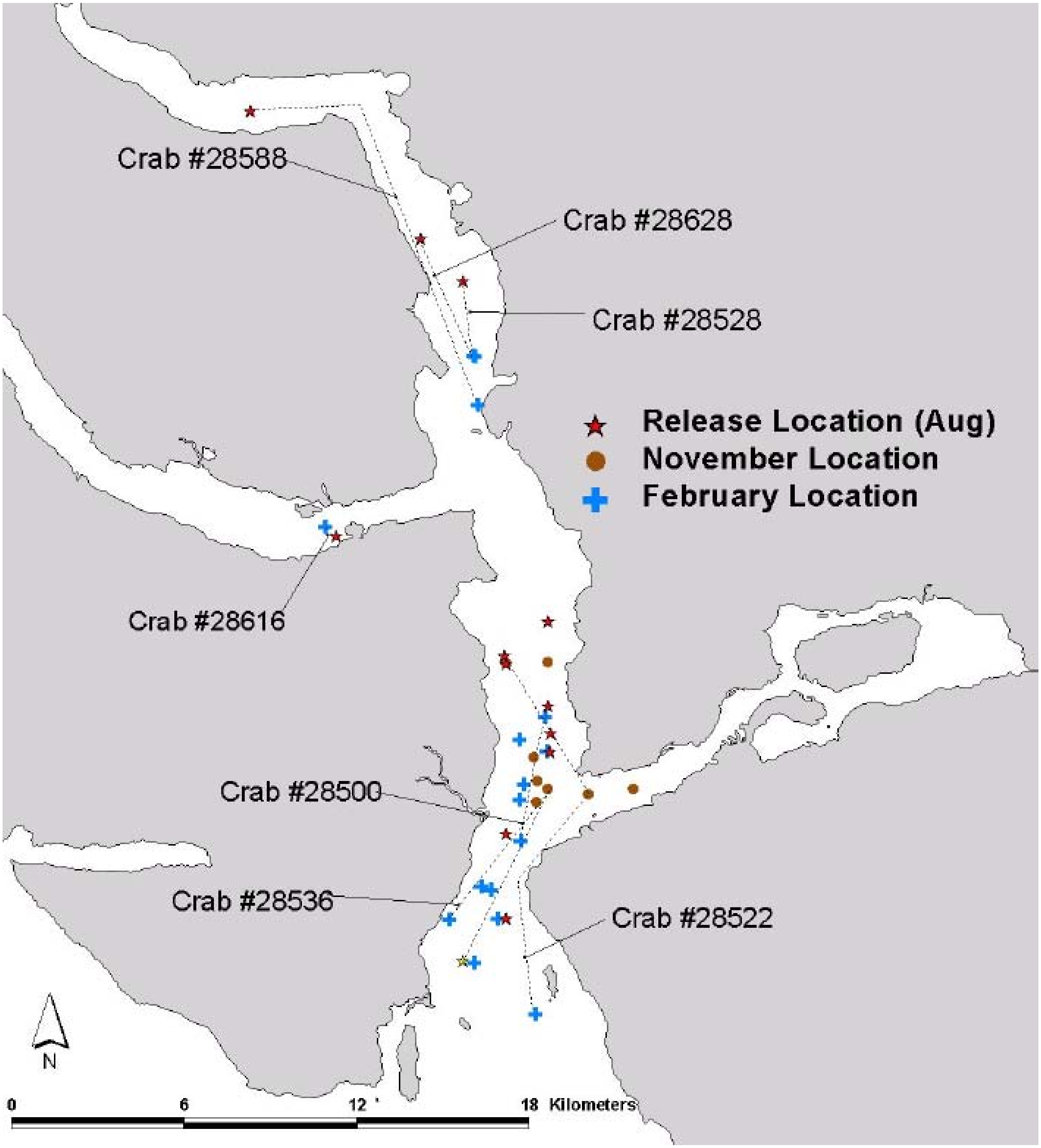


Figure 15. Release locations (August 2002) and estimated subsequent positions (November 2002 and February 2003) for sonic tagged Tanner crabs. Dashed lines demonstrate possible movement paths for selected Tanner crabs based on estimated positions.

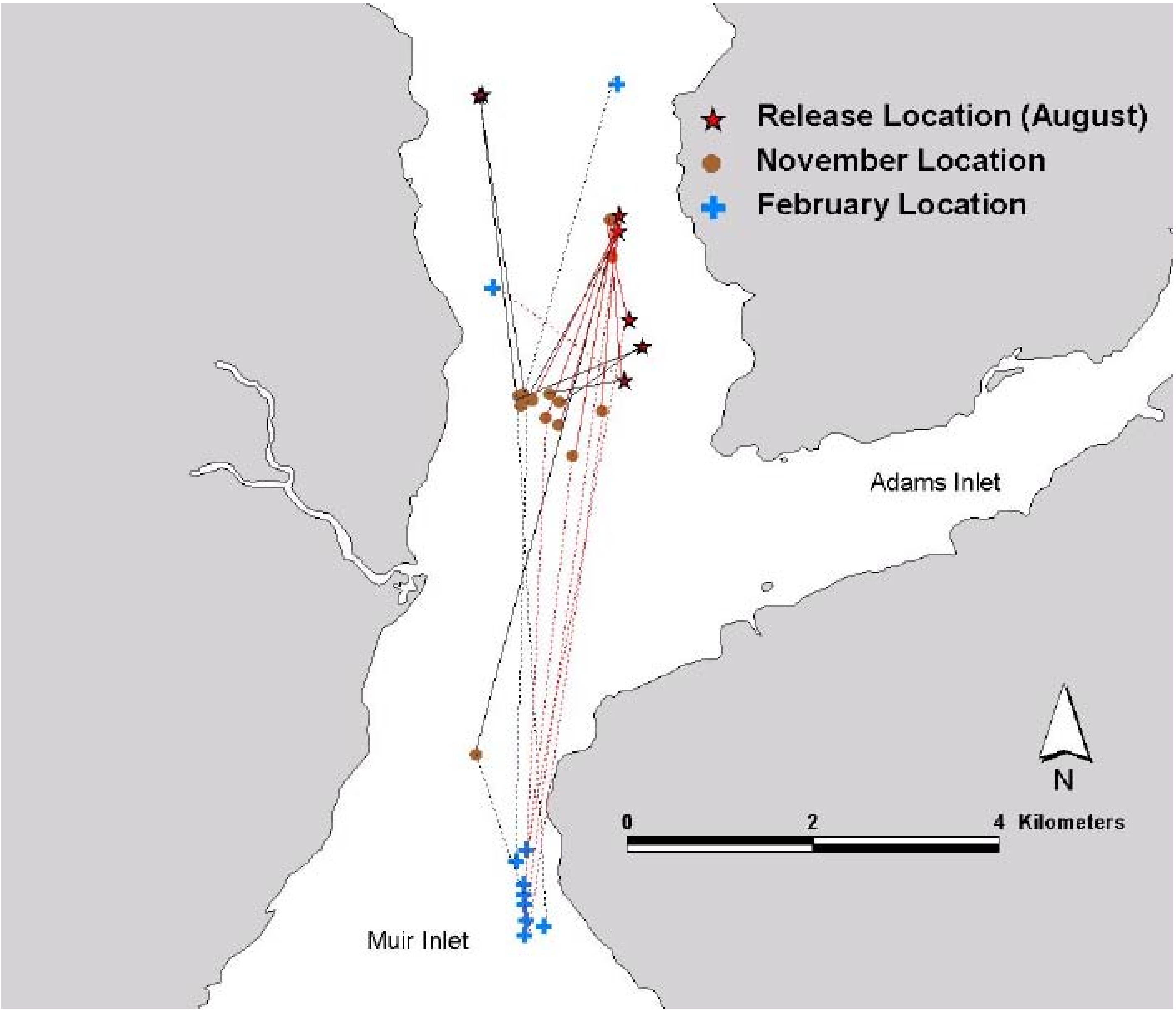


Figure 16. Release locations (August 2002) and estimated subsequent positions (November 2002 and February 2003) for sonic tagged red king crabs. Lines demonstrate possible movement paths based on estimated positions. Paths for females are black and paths for males are red. Solid lines represent estimated movement between August and November 2002 and dashed lines represent estimated movement between November 2002 and February 2003.