Abstract—Dungeness crabs (*Cancer magister*) were sampled with commercial pots and counted by scuba divers on benthic transects at eight sites near Glacier Bay, Alaska. Catch per unit of effort (CPUE) from pots was compared to the density estimates from dives to evaluate the bias and power of the two techniques. Yearly sampling was conducted in two seasons: April and September, from 1992 to 2000. Male CPUE estimates from pots were significantly lower in April than in the following September; a step-wise regression demonstrated that season accounted for more of the variation in male CPUE than did temperature. In both April and September, pot sampling was significantly biased against females. When females were categorized as ovigerous and nonovigerous, it was clear that ovigerous females accounted for the majority of the bias because pots were not biased against nonovigerous females. We compared the power of pots and dive transects in detecting trends in populations and found that pots had much higher power than dive transects. Despite their low power, the dive transects were very useful for detecting bias in our pot sampling and in identifying the optimal times of year to sample so that pot bias could be avoided.

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Estimating Dungeness crab (*Cancer magister*) abundance: crab pots and dive transects compared

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Reliable population assessments are fundamental to the management and conservation of commercially harvested crabs. Many crab populations are sampled with commercial crab pots to estimate population trends, to set harvest quotas, or to differentiate natural population fluctuations caused by anthropogenic changes to the ecosystem. Pots are used, for example, to assess the population status of blue crabs, *Callinectes sapidus* (Abbe and Stagg, 1996), red king crabs, *Paralithodes camtschaticus* (Zheng et al., 1993), snow crabs, *Chionoecetes opilio* (Dawe et al., 1996), and southern king crabs, *Lithodes santolla* (Wyngaard and Iorio, 1996).

The Dungeness crab (*Cancer magister*) fishery began in southeastern Alaska in 1916 and has been characterized by large fluctuations on annual and decadal scales (Orensanz et al., 1998). Large variation in the Dungeness crab harvest is not unique to Alaska; similar fluctuations have been documented in California and their causes are the subject of an ongoing debate (Higgins et al., 1997a, 1997b). It is not clear whether the processes that cause fluctuations in California are the same as those responsible for oscillations in Dungeness crab abundance in Alaska.

Most of the Dungeness crab fisheries in Alaska are managed by regulating the size and sex of the crabs caught, and, in some places, the season of the harvest. In southeastern Alaska, legal harvest is restricted to males with a carapace width greater than or equal to 165 mm (excluding the 10th anteriolateral spines) and the season is timed to avoid sensitive life

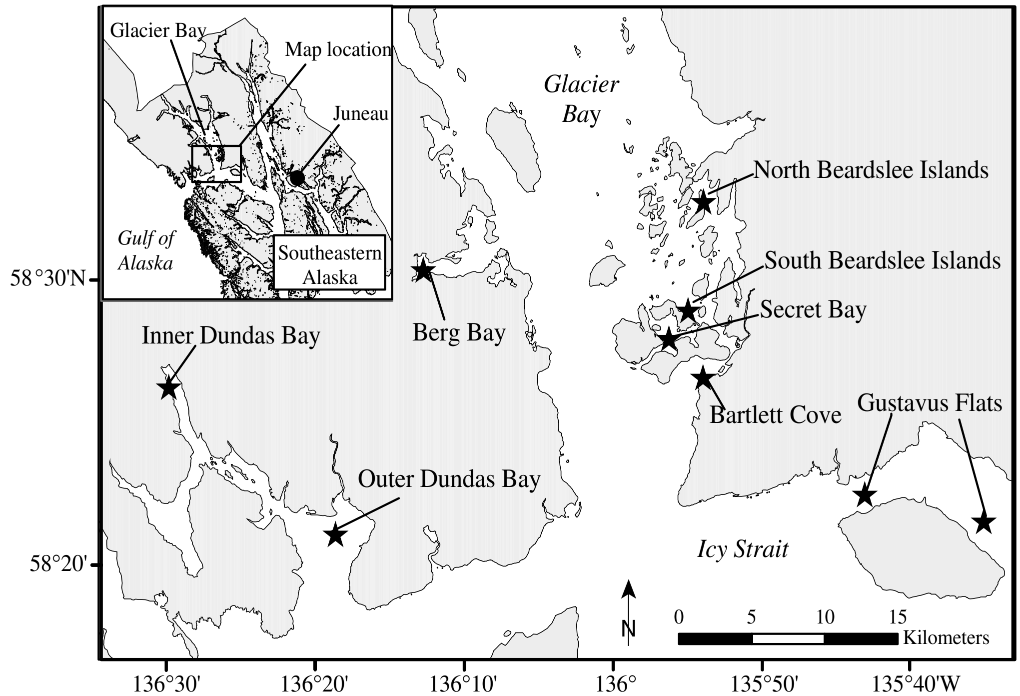

Figure 1

Map of study area showing eight study sites in or near Glacier Bay in southeastern Alaska.

history periods such as mating and molting (Kruse, 1993; Orensanz et al., 1998). Pre- and postseason stock assessment surveys using crab pots were initiated in southeastern Alaska in 2000 (Rumble and Bishop, 2002). The purpose of the latter management strategy is to assess the abundance of legal-size males before the fishing season, to estimate harvest rates, to define the timing of male and female mating and molting and to determine growth rate by tagging crabs.

The usefulness of surveys with pots for Dungeness crab population assessment, however, depends on the accuracy of these surveys in measuring population parameters. Factors that can bias catch per unit of effort (CPUE) and size-frequency estimates for Dungeness crabs are pot soak-time (Miller, 1974; High, 1976; Gotshall, 1978; Smith and Jamieson, 1989); freshness of bait (High, 1976; Smith and Jamieson, 1989); pot design (Miller, 1974; High, 1976; Smith and Jamieson, 1989); and agonistic interactions among conspecifics inside and at the entrance of pots (Caddy, 1979; Smith and Jamieson, 1989). Smith and Jamieson (1989) developed a standardized model to compensate for the effect of agonistic interactions, age of bait, and escapement. They also concluded that researchers could minimize these biases by measuring CPUE with standardized surveys with short soak times. These studies measured sampling bias with pots by comparing catch in pots among various experimental treatments. Opportunities for comparing surveys with pots to direct measures of abundance are rare. In our study, we compared the bias and power of CPUE estimates from surveys with pots to independent measures of abundance conducted by scuba divers on benthic dive transects.

Methods

Study area

The study area included eight sites in southeastern Alaska, near Glacier Bay: North Beardslee Islands (58°33′N 135°54′W), South Beardslee Islands (58°30′N 135°55′W), Berg Bay (58°31′N 136°13′W), Bartlett Cove (58°27′N 135°53′W), Gustavus Flats (58°23′N 135°43′W), Secret Bay (58°29′N 135°56′W), inner Dundas Bay (58°27′N 136°31′W), and outer Dundas Bay (58°21′N 136°18′W) (Fig. 1). All study sites were located within Glacier Bay National Park and Preserve, with the exception of Gustavus Flats, which was located adjacent to the Park boundary in Icy Strait.

Glacier Bay is a large (1312 km^2) glacial fjord system with high sedimentation rates of clay-silt particles from streams and tidewater glaciers (Cowan et al., 1988). The primarily unconsolidated rocky coastline is highly convoluted with numerous small bays. Dungeness crabs can be found throughout Glacier Bay; however the majority of the population are found in the lower 40 km of the estuary where our sites were located (Taggart et al., 2003). The shallow water in and around our study sites was primarily characterized by mud bottom, but sand, pebble, cobble, and shell substrates were also common (Scheding et al., 2001).

Table 1

Sampling dates for yearly spring and fall pot and dive surveys of Dungeness crabs (*Cancer magister*) in Glacier Bay, Alaska. Sample size (*n*) is listed for pots and dives for each sampling event.

	Spring sampling				Fall sampling			
Year	Pots	*n*	Dives	*n*	Pots	*n*	Dives	*n*
1992	7–12 April	248	7–12 April	69	17–22 Sept.	250	17–22 Sep.	75
1993	20–27 April	350	20–27 April	105	23–28 Sept.	250	23–28 Sep.	75
1994	20–27 April	350	23 April–1 May	105	13–18 Sept.	249	13–18 Sept.	75
1995	19–26 April	350	23 April–1 May	105	9–14 Sept.	236	15–19 Sept.	75
1996	15–21 April	350	22–28 April	105	13–18 Sept.	242	19–23 Sept.	73
1997	17–22 April	300	23–28 April	115	14–19 Sept.	298	20–25 Sept.	120
1998	—	—	—	—	9–14 Sept.	296	16–21 Sept.	91
1999	—	—	—	—	9–14 Sept.	299	17–22 Sept.	107
2000	—	—	—	—	9–14 Sept.	297	18–23 Sept.	60

Sampling dates

Sampling was conducted biannually, in April and September, from 1992 to 1997 and annually, in September, from 1998 to 2000 (Table 1). The spring and fall sampling periods were selected to coincide with crab life history events and to avoid sampling during commercial fishery operations. April sampling was scheduled to occur before larval hatching in May–June (Shirley et al., 1987) and before the summer commercial fishing season from 15 June to 15 August. September sampling began after the end of the fishing season (15 August) and ended before the beginning of the winter harvest (1 October to 30 November).

During 1992, the study sites were sampled with pots (referred to as "pot sampling") and by divers (referred to as "dive sampling") concurrently (Table 1). In 1993 and 1994, sampling was conducted on nearby study sites and the dive sampling usually one day ahead of the pot sampling. For logistical reasons, starting in 1995, we separated the pot sampling and the dive-transect sampling into two separate research cruises. The pot sampling was conducted on the first cruise and the dive sampling occurred on the second cruise; pot and dive sampling were separated at each location by 2 to 12 days.

Sampling with pots

Crabs were sampled with commercial crab pots (0.91 m in diameter, 0.36 m tall, with 5-cm wire mesh). Escape rings were sealed with webbing on each pot to retain smaller crabs. Pots were baited with hanging bait comprising salmon, cod, or halibut (depending on availability) and bait jars that were filled with chopped herring and squid. We found that cod was predictably available; therefore from 1996 on, we consistently used cod for hanging bait. Pots were soaked for 24 hours.

Within each study site, we set 25 pots in shallow water (0–9 m) and 25 pots in deep water (10–25 m). Each day we set 50 pots in one of the study sites and retrieved the 50 pots that had been set the previous day at one of the other study sites. The pots were set along strings parallel to shore at intervals of approximately 100 m. Within each study area, the strings of pots were located in prime Dungeness crab habitat determined by a local fisherman. We placed the pots at the same locations during subsequent sampling events by using a GPS (Rockwell PLGR+) with an accuracy of ±3 m. We estimate that the pots were set within 20 meters from the original waypoints. Water depth (standardized to mean lower low water), set and retrieval time, and GPS location were recorded for each pot. Water temperature and salinity profiles were measured at each study site during each sampling period with a SEABIRD SBE-19 Profiler.

As the pots were retrieved, we counted and identified all organisms. For all Dungeness crabs we recorded the sex, carapace width, shell condition, and damage to appendages. For female crabs we also recorded reproductive status. Carapace width was measured to the nearest millimeter immediately anterior to the 10th anterolateral spine with vernier calipers (Shirley and Shirley, 1988; Shirley et al., 1996). All organisms were returned to the water at the location where they were caught. A potential problem with returning the crabs to the water near the site of capture is the possibility that crabs could be resampled in subsequent pots, which would bias the catch per unit of effort. Beginning in April, 1995, all crabs collected in the South Beardslee Islands and Berg Bay were tagged with a sequentially numbered, double-T Floy tag (Floy Tag and Manufacturing Company, Seattle, WA) inserted along the posterolateral margin of the epimeral suture. Tags placed in this location are retained through ecdysis (Smith and Jamieson, 1989). Of the 5226 crabs tagged, only a single crab was recovered during the same sampling event. Thus, the probability of resampling crabs by returning them to the water was very low.

Sampling by divers

Divers using scuba equipment censused crabs on 15 to 20, 2×100 m belt transects within each study site. Approximately one day of sampling was required at each study site. The dive transects were conducted perpendicular to the shoreline and they extended from the shallow subtidal (0 m, mean lower low water) to 18 m depth or to the end of the 100 m transect, whichever came first. Divers did not go below 18 m depth in an effort to reduce nitrogen accumulation in divers' blood and to reduce the surface intervals required between transects. From 1992 to 1997, transect locations were randomly selected in the same areas as the crab-pot sampling. The random locations selected in 1997 were resampled during the following years of the study.

Divers counted all Dungeness crabs located within 1 m of each side of the transect. An effort was made to locate buried crabs by swimming close to the bottom and looking for irregularities in the bottom or protruding crab eyestalks. Each crab was examined and the following were recorded: legal males ≥165 mm carapace width), sublegal males (<165 mm carapace width), ovigerous females, and nonovigerous females.

Data analysis

For each year, we calculated the average pot CPUE for each site by reproductive class (males, nonovigerous females, and ovigerous females). The number of pots sometimes deviated from 50 when a pot was lost or when the degradable cotton string securing the pot lid broke (range: 44–50 pots). The number of crabs counted on dive transects was averaged for each reproductive class by site for each year. All dive transects were conducted perpendicular to shore; thus the transects crossed the shallow habitat where the shallow string of pots was set and terminated at 18 m which was the center of the depth we targeted for the deep pot set. Because the deep pot set was at or slightly beyond the deep end of the transect, we may have sampled more crabs from deepwater habitats than from the shallower transects. However, we did not think this was a significant bias because we sampled crabs from a relatively large area. We, therefore, pooled the pots from both depth strata for analysis.

We tested for differences between April and September for the pot CPUE data and the dive density data with paired *t*-tests. CPUE and density data were not normally distributed; therefore we transformed the data with a square-root transformation $[Y=\sqrt{(Y+3/8)}]$ for statistical analyses (Zar, 1996). These analyses were conducted for males, nonovigerous females, and ovigerous females. Because seasonal increases in water temperature could drive differences in CPUE between April and September, we calculated mean water temperatures by averaging the water temperatures at the 5 m and 15 m depths at each site and year. This analysis was limited to years and sites where we collected samples in both April and September (1992–97, from five sites: North Beardslee Islands, South Beardslee Islands, Berg Bay, Bartlett Cove, and Gustavus Flats). We assessed how CPUE was influenced by two independent variables, water temperature and season, with stepwise regression. Because CPUE declined from 1992 to 1997 (Taggart et al., in press), we controlled for year so that it would not confound our analysis.

In order to assess sampling bias between pots and dive transects, the percentages of females (females/all crabs), nonovigerous females (nonovigerous females/all crabs), and ovigerous females (ovigerous females/all crabs) were calculated for each site and sampling time. We also compared the percentage of the male population that was legal size (legal-size male crabs/all male crabs) from the pots and from the dives. The percentage estimates from the pot data were compared to estimates from the dive transects with a paired sign test (Zar, 1996). If percentage estimates for pot data were unbiased when compared to estimates from dive data, the pot percentage estimates would have an equal chance of being higher or lower than the percentage estimates for the dive data. Because small sample sizes exaggerate percentage comparisons, we excluded samples where the total number of crabs collected was less than 25 crabs/site.

The power of pots and dive transects to detect trends in populations was compared with Monitor, a power analysis program (Gibbs and Melvin, 1997; Gibbs, 1998). For our analyses, we varied the number of transects and pots, compared males and nonovigerous females, and varied the duration of the study. For all analyses the following input parameters of the model were held constant: "survey occasions" = annual, "type" = linear, "significance level" = 0.05, "number of tails" = 2, "constant added" = 1, "trend variation" = 0, "rounding" = decimal, "trend coverage" = complete, and "replications" = 10,000.

To estimate power, the model requires "count" and "variance" for each plot across years for at least three years. Pot and transect data collected from 1992 to 1998 from five sites (North Beardslee Islands, South Beardslee Islands, Berg Bay, Bartlett Cove, and Gustavus Flats) were used for these analyses. The data were limited to September to avoid seasonal bias. The average across years was calculated for each transect and each pot. These averages were input into the model's variable called "plot count." For each pot and transect a linear regression was calculated among years (CPUE vs. year for pots; density vs. year for dive transects) and the residual mean square was the "plot variance" variable (Thomas and Krebs, 1997).

To estimate the effect of sample size on power we set the "number [surveys] conducted" to four and limited the analysis to males. We varied the number of "plots" (pots and transects). For pots, we randomly selected subsamples of the 250 pots and ran simulations from 25 pots to 250 pots in 25-pot increments. The number of dive transects for which data were collected for multiple years was 75. For simulations with a sample size less than 75, we randomly subsampled the data in the same manner as we did with pots. For simulations with sample sizes greater than 75, we amplified the samples with simple bootstrapping to obtain samples from 100 to 250 transects in 25-transect increments (Wonnacott and Wonnacott, 1990). For each sample size, we modeled three annual rates of change (0.02, 0.03, and 0.05).

To evaluate how study duration affects power, we limited the analysis to males, varied study duration ("number [surveys] conducted") from two years to 12 years in two-year increments, and compared three annual rates of change (0.02, 0.03, and 0.05) for both pots and transects. To hold effort constant between the two sampling techniques, we set the pot and transect sample size to the number we could accomplish in a five-day research cruise (250 pots and 75 transects).

To explore the relationship between annual trend in population and power, we held effort constant (250 pots and 75 transects) and varied the annual trend (from −0.10 to +0.10 in 0.01 increments) for both males and nonovigerous females. It was not possible to conduct a power analysis for ovigerous females because a large proportion of the pots and transects had no ovigerous female crabs.

Results

The pot CPUE estimates for males, nonovigerous females, and ovigerous females was significantly different in April than in the following September (Fig. 2, A, C, and E). Male and nonovigerous female CPUE was higher in September (Fig. 2, A and C) and ovigerous female CPUE was lower in September (Fig. 2E). In contrast, April density estimates from dive transects were not significantly different from the following September density estimates for males (Fig. 2B). Dive density estimates for nonovigerous females were higher in September than in April (Fig. 2D); density estimates for ovigerous females were lower in September than in April (Fig. 2F).

When we tested the influence of temperature and season on male CPUE with stepwise regression, season was selected first; temperature was not selected because it did not have a significant additional effect (Table 2). Because no significant difference was found between the April and September density estimates from dive transects (Fig. 2B), we did not conduct a stepwise regression for the dive data.

Percentage estimates of females from sampling with pots were lower than percentage estimates from dive transects for a significant number of samples for both April and September (Fig. 3A); therefore pots were biased against sampling females. When females were split by reproductive status, no bias was detected for sampling nonovigerous females with pots (Fig. 3B). In contrast, the percentage estimates for ovigerous females remained biased and the magnitude of the bias increased (Fig. 3C). To test potential sampling bias

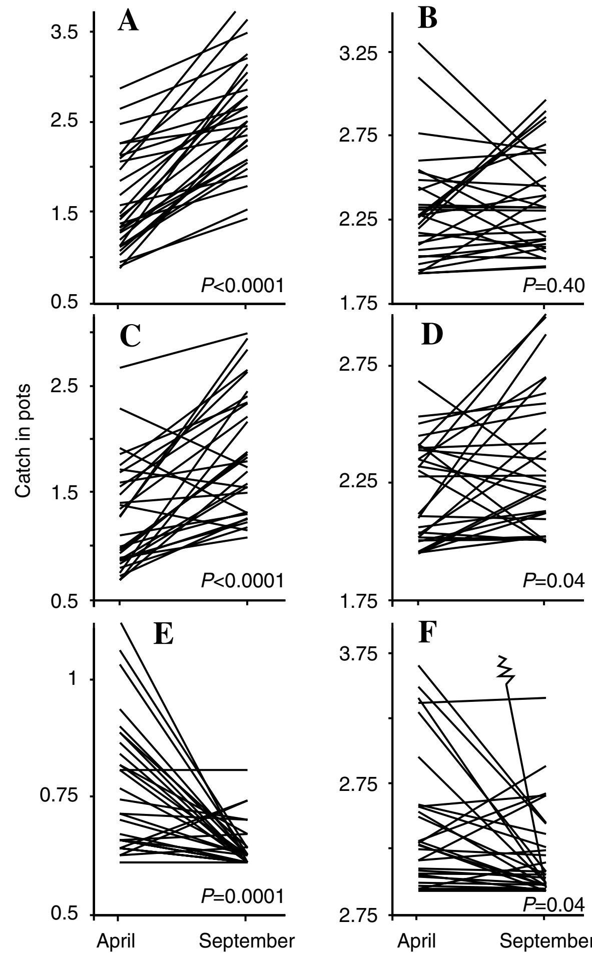

Figure 2

Within-year paired comparisons by site of catch in pots (left column) and density on dive transects (right column) for: (**A** and **B**) male Dungeness crabs (*Cancer magister*); (**C** and **D**) nonovigerous female crabs; and (**E** and **F**) ovigerous female crabs. Catch and density data were transformed with a square-root transformation. *P*-values indicate results from paired *t*-tests and significant results show differences between April and September. Lines on the graphs are parallel if measurements at sites were consistently higher or lower in April and September.

related to crab size, we compared the proportion of the male population that was legal size sampled with pots and dives (Fig. 4). There was no significant bias when pots and transects were compared with a sign test (April, $P>0.999$; September, $P=0.06$).

CPUE estimates from pots had a higher power than density estimates from dive transects for the same sample size (Fig. 5). Because more time is required to conduct a dive transect than to set and pull a crab pot, the power of transects compared to pots was even lower when effort was incorporated into the analysis (Fig 6). The power can be increased for both pots and

Table 2

Stepwise regression results of CPUE (male crabs/pot) versus three independent variables (year, season, and temperature).

Step	Model parameters	r^2	*P*-value (parameter)
1	*Year*	0.1493	0.001 (year)
2	*Year* and *month*	0.5589	0.04 (month)
3	*Year, month,* and *temperature*	0.5589	0.98 (temperature)

transects by increasing the study duration or increasing the amount of change in the population that the study is attempting to detect (Fig. 6). Although pots had more power than dive transects, there was only slightly more power to detect change in abundance of male crabs versus nonovigerous females (Fig. 7).

Discussion

For male Dungeness crabs, the density estimates from the dive transects showed no difference between April and September (Fig. 2B). The male CPUE estimates from pots, however, were consistently lower in April than in the following September (Fig. 2A). Because feeding rates of Dungeness crabs are correlated with temperature (Kondzela and Shirley, 1993), we thought that temperature was likely to explain the differences in CPUE between April and September. We found, however, that season had a larger effect than temperature (Table 2). This result suggests that seasonal factors other than temperature influence catchability. Stone and O'Clair (2001) followed the seasonal movements of Dungeness crabs in a glacial estuary in southeastern Alaska and reported that mean movement of male crabs was lower during the spring than in the late summer and fall. It is possible that our spring sampling schedule coincided with low male activity and male crabs were less likely to encounter a bait plume and be attracted to a pot. These results indicate that if pots are used for sampling, late summer and early fall is the time of year to conduct population assessment surveys of male crabs. Similar seasonal differences in CPUE have also been described for edible crabs (*Cancer pagurus*) and American lobsters (*Homarus americanus*) (Bennett, 1974). These data demonstrate the importance of controlling for season when comparing CPUE among years or sites.

The proportion of large crabs caught in pots increased with longer soak time for Dungeness crabs in British Columbia (Smith and Jamieson, 1989) and red king crabs in Britstol Bay, Alaska (Pengilly and Tracy, 1998). We found no bias when we measured the legal-size proportion of the male population caught in pots and compared it to the proportion sampled on dives (Fig. 4). We expect, however, that the bias observed in British Columbia and Bristol Bay would occur for our study sites if the soak time of pots were increased.

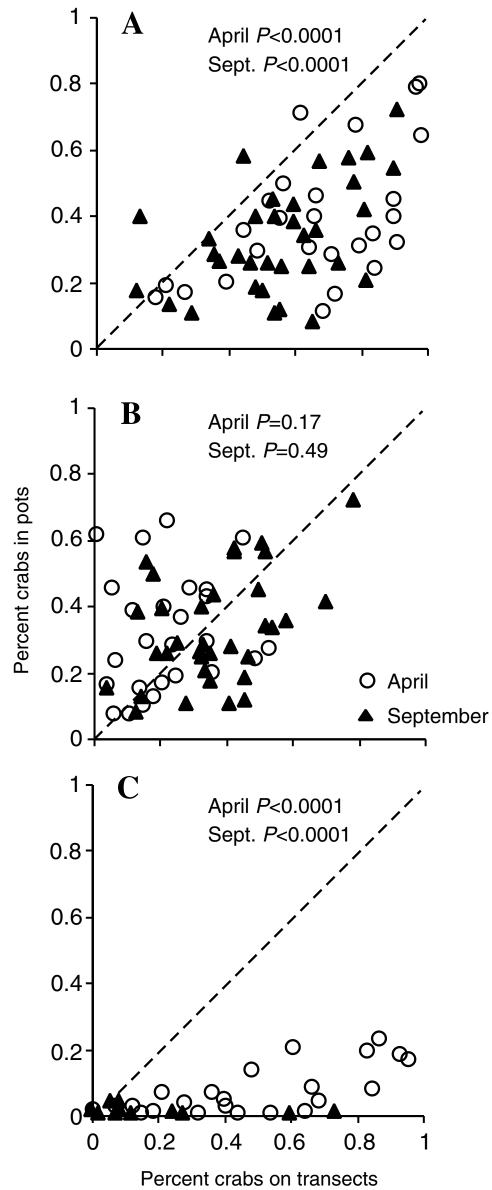

Figure 3

The percentage of (**A**) female Dungeness crabs (*C. magister*), (**B**) nonovigerous female crabs, and (**C**) ovigerous female crabs estimated from pots and from dive transects. The dashed line in each graph has a slope of 1; thus half of the data points should be above and half should be below the dashed line if percentage estimates for dives and pots are unbiased. Pot and dive transect data for each sex class and season were compared with a paired sign test and *P*-values are reported.

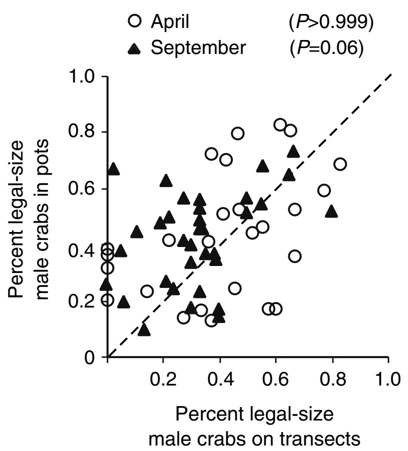

Figure 4

The percentage of male crabs of the Dungeness crab (*C. magister*) population that were legal size (≥165 mm) estimated from pots compared to the percentage of male crabs estimated from dive transects. Data from pots and dive transects were compared for each season with a paired sign test and *P*-values are reported.

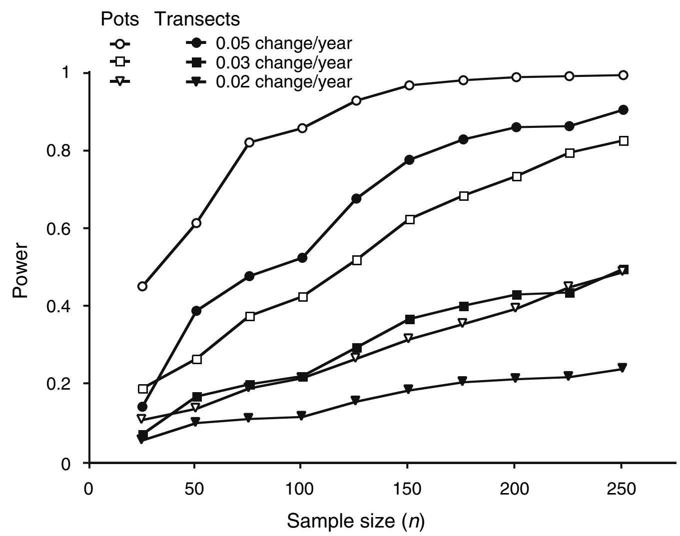

Figure 5

Relationship between power and sample size (n) in comparing catch from pots and density on dive transects for male Dungeness crabs (*C. magister*) at three levels of population change.

In both April and September, pot sampling was significantly biased against females (Fig. 3A). When females were categorized as ovigerous and nonovigerous, it was clear that ovigerous females accounted for the majority of the bias because pots were not biased against nonovigerous females (Fig. 3B). Similar results have been found for a closely related species, *Cancer pagurus*; female *C. pagurus* readily enter pots when they are in a nonovigerous reproductive state but are rarely captured when they are ovigerous (Bennett, 1995). Movement studies of Dungeness crabs tagged with sonic transmitters have demonstrated that ovigerous females move less frequently and move slower than males or nonovigerous females (O'Clair et al., 1990). Thus, one explanation for the bias against ovigerous female crabs is that their restricted movements make it less likely they will be able to locate and become entrapped in pots. In addition to being less mobile, ovigerous females may be less attracted to bait than nonovigerous crabs. In controlled feeding experiments, ovigerous females had lower feeding rates than nonovigerous females, and ovigerous females took longer to begin feeding (Schultz et al., 1996; Schultz and Shirley, 1997). Therefore, ovigerous females may be less responsive to the bait plume from a pot.

The estimate of nonovigerous females from both pot CPUE and dive transect density increased from April to September (Fig. 2, C and D). As with males, the increase in CPUE for nonovigerous females may be partly due to an increase in catchability in September. However, the fact that the density estimates from dives also increased suggests that the number of nonovigerous females actually increased between April and September. This explanation is supported by the decrease in ovigerous crabs from April to September for both CPUE (Fig. 2E) and density estimates (Fig. 2F).

The low catchability of ovigerous females makes it problematic to monitor relative abundance of females or changes in sex ratio through time. However, because pots were not biased against nonovigerous females (Fig. 3), the solution may be to estimate the relative abundance of females by sampling after females hatch their eggs and before they extrude a new clutch of eggs in the fall. In southeastern Alaska, most females are nonovigerous in late July and early August (Stone and O'Clair, 2001; Swiney et al., 2003); therefore this would be the optimal time of year to sample females or to measure sex ratio of Dungeness crab populations. Unfortunately, this timing coincides with the summer commercial fishing season, which could bias sampling if there was "competition" between survey pots and commercial pots.

For both males and females, the power analyses of the pot and dive data indicated that for most population assessment applications it would be extremely difficult to conduct enough dive transects to obtain sufficient statistical power. Even if it were possible to conduct as many dive transects as pot samples, the power of a dive transect was still lower than that of a pot; the higher power of the pots was due to lower variance among pots. Pots work by attracting crabs with a bait plume; thus the area and number of crabs sampled is

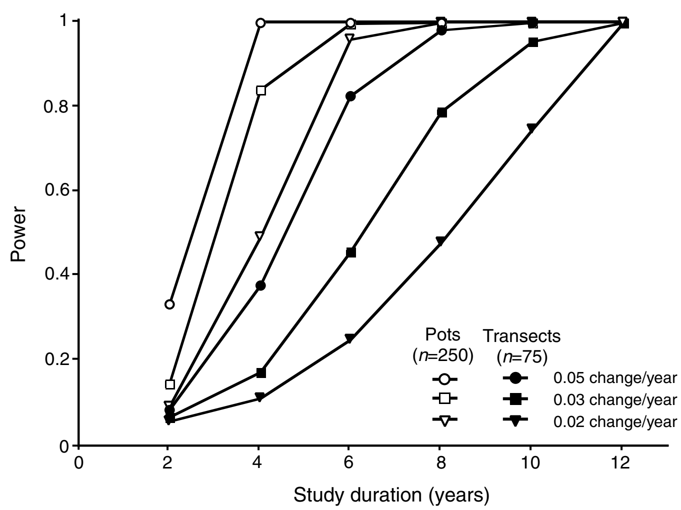

Figure 6

Relationship between power and study duration in comparing catch from crab pots and density on dive transects for male Dungeness crabs (*C. magister*) at three levels of population change. To hold effort constant, we set the sample size (*n*) to the number of pots and dives that could be accomplished in five days.

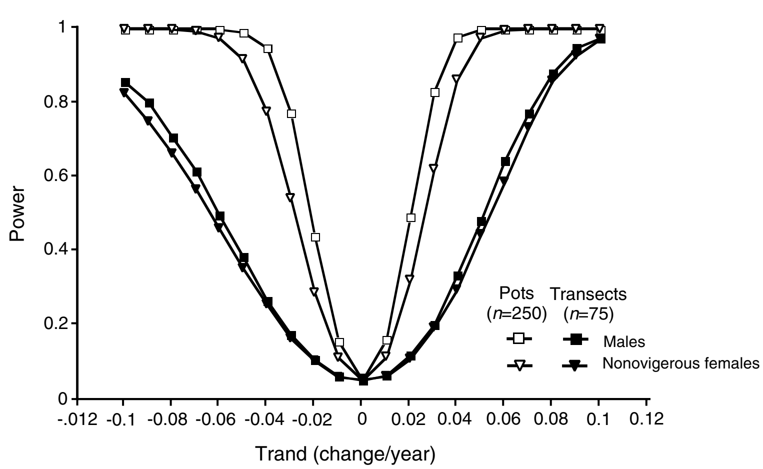

Figure 7

Relationship between power and trend in population in comparing catch in crab pots and density on dive transects for male and nonovigerous female Dungeness crabs (*C. magister*).

larger with pots than with transects and the variance with pots is lower.

Despite their low power, the independent measures of abundance provided by dives helped us identify bias in our Dungeness crab survey method. Our analysis of these two techniques demonstrates that it is possible to avoid most biases with pots if sampling is conducted at optimal times of year. Similar comparisons could be conducted in other areas to identify sampling biases so that they could be minimized and important parameters, such as abundance, size, and sex ratio, could be monitored effectively.

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Literature cited

Abbe, G. R., and C. Stagg.
1996. Trends in blue crab (*Callinectes sapidus* Rathbun) catches near Calvert Cliffs, Maryland, from 1968 to 1995 and their relationship to the Maryland commercial fishery. J. Shellfish Res. 15:751–758.

Bennett, D. B.
1974 The effects of pot immersion time on catches of crabs, *Cancer pagurus* L. and lobster, *Homarus gammarus* (L.). J. Cons. Int. Explor. Mer 35:332–336.
1995. Factors in the life history of the edible crab (*Cancer pagurus* L.) that influence modelling and management. ICES Mar. Sci. Symp. 199:89–98.

Caddy, J. F.
1979. Some considerations underlying definitions of catchability and fishing effort in shellfish fisheries, and their relevance for stock assessment purposes. Manuscript Report, 1489, 1–18 p. Department of Fisheries and Oceans Canada, Halifax, Nova Scotia, Canada.

Cowan, E. A., R. D. Powell, and N. D. Smith.
1988. Rainstorm-induced event sedimentation at the tidewater front of a temperate glacier. Geology 16: 409–412.

Dawe, E. G., D. M. Taylor, and J. M. Hoenig.
1996. Evaluating an index of snow crab *(Chionocetes opilio)* biomass from trapping surveys. *In* Proceedings of the international symposium on biology, management, and economics of crabs from high latitude habitats, Anchorage, Alaska, October 11–13, 1995, vol. 96-02, p. 301–314. Alaska Sea Grant College Program, Univ. Alaska, Anchorage, AK.

Gibbs, J. P.
1998. Monitoring populations of plants and animals. BioScience 48:935–940.

Gibbs, J. P., and S. M. Melvin.
1997. Power to detect trends in water bird abundance with call-response surveys. J. Wildl. Manag. 61(4): 1262–1267.

Gotshall, D. W.
1978. Catch-per-unit-of-effort studies of northern California Dungeness crabs, *Cancer magister*. Calif. Fish Game 64(3):189–199.

Higgins, K., A. Hastings, and L. W. Botsford.
1997a. Density dependence and age structure: nonlinear dynamics and population behavior. Am. Nat. 149(2):247–269.

Higgins, K., A. Hastings, J. N. Sarvela, and L. W. Botsford.
1997b. Stochastic dynamics and deterministic skeletons: population behavior of Dungeness crab. Science 276(5317):1431–1435.

High, W. L.
1976. Escape of Dungeness crabs from pots. Mar. Fish. Rev. 38(4):19–23.

Kondzela, C. M., and T. C. Shirley.
1993. Survival, feeding, and growth of juvenile Dungeness crabs from southeastern Alaska reared at different temperatures. J. Crustacean Biol. 13(1):25–35.

Kruse, G. H.
1993. Biological perspectives on crab management in Alaska. *In* Proceedings of the international symposium on management strategies for exploited fish populations (G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II, eds.), 355–384 p. Lowell Wakefield Fisheries Symposium. Alaska Sea Grant College Program Report 93-02, Univ. Alaska, Fairbanks, AK.

Miller, R. J.
1974. Saturation of crab traps: reduced entry and escapement. J. Cons. Int. Explor. Mer 38(3):338–345.

O'Clair, C. E., R. P. Stone, and J. L. Freese.
1990. Movements and habitat use of Dungeness crabs and the Glacier Bay fishery. *In* Second Glacier Bay science symposium, Glacier Bay National Park & Preserve, AK, Sept. 19–22, 1988 (A. M. Milner and J. D. Wood Jr., eds.), 74–77 p. U.S. National Park Service, Anchorage, AK.

Orensanz, J. M., 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.

Pengilly, D., and D. Tracy.
1998. Experimental effects of soak time on catch of legal-sized and nonlegal red king crab by commercial king crab pots. Alaska Fish. Res. Bull. 5(2):81–87.

Rumble, J., and G. Bishop.
2002. Report to the Board of Fisheries, Southeast Alaska Dungeness Crab Fishery. Alaska Department of Fish and Game, Regional Information Report 1J02-45, p. 2.2–2.16. Alaska Dep. Fish and Game, Juneau, AK.

Scheding, K., T. C. Shirley, C. E. O'Clair, and S. J. Taggart.
2001. Critical habitat for ovigerous Dungeness crabs. *In* Spatial processes and management of fish populations October 27–30 (G. H. Kruse, N. Bez, A. Booth, M. W. Dorn, S. Hills, R. N. Lipcius, D. Pelletier, C. Roy, S. J. Smith, and D. Witherell, eds.), 431–446 p. Alaska Sea Grant, report AK-SG-01-02. Univ. Alaska, Fairbanks, AK.

Schultz, D. A., and T. C. Shirley.
1997. Feeding, foraging and starvation capability of ovigerous Dungeness crabs in laboratory conditions. J. Crustacean Res. 26:26–37.

Schultz, D. A., T. C. Shirley, C. E. O'Clair, and S. J. Taggart.
1996. Activity and feeding of ovigerous Dungeness crabs in Glacier Bay, Alaska. *In* High latitude crabs: biology, management, and economics, October 11–13, 1995, vol.

96-02, p. 411–424. Alaska Sea Grant College Program, AK-SG-96-02, Univ. Alaska, Anchorage, AK.

Shirley, S. M., and T. C. Shirley.
1988. Appendage injury in Dungeness crabs, *Cancer magister*, in southeastern Alaska. Fish. Bull. 86:156–160.

Shirley, T. C., G. Bishop, C. E. O'Clair, S. J. Taggart, and J. L. Bodkin.
1996. Sea otter predation on Dungeness crabs in Glacier Bay, Alaska. *In* High latitude crabs: biology, management, and economics, 563–576 p. Lowell Wakefield Fisheries Symposium. Alaska Sea Grant College Program Report 96-02, Univ. Alaska, Fairbanks, AK.

Shirley, S. M., T. C. Shirley, and S. D. Rice.
1987. Latitudinal variation in the Dungeness crab, *Cancer magister*: zoeal morphology explained by incubation temperature. Mar. Biol. 95(3):371–376.

Smith, B. D., and G. S. Jamieson.
1989. A model for standardizing Dungeness crab (*Cancer magister*) catch rates among traps which experienced different soak times. Can. J. Fish. Aquat. Sci. 46:1600–1608.

Stone, R. P., and C. E. O'Clair.
2001. Seasonal movements and distribution of Dungeness crabs, *Cancer magister*, in a glacial southeastern Alaska estuary. Mar. Ecol. Prog. Ser. 214:167–176.

Swiney, K. M., T. C. Shirley, S. J. Taggart, and C. E. O'Clair.
2003. Dungeness crab, *Cancer magister*, do not extrude eggs annually in southeastern Alaska: An *in situ* study. J. Crustacean Biol. 23(2):280–288.

Taggart, S. J., P. N. Hooge, J. Mondragon, E. R. Hooge, and A. G. Andrews.
2003. Living on the edge: the distribution of Dungeness crab, *Cancer magister*, in a recently deglaciated fjord. Mar. Ecol. Prog. Ser. 246:241–252.

Taggart, S. J., T. C. Shirley, C. E. O'Clair, and J. Mondragon.
In press. Dramatic increase in the relative abundance of large male Dungeness crabs, *Cancer magister*, following closure of commercial fishing in Glacier Bay, Alaska. *In* Aquatic protected areas as fisheries management tools (J. B. Shipley, ed.). Am. Fish. Soc., Bethesda, MD.

Thomas, L., and C. J. Krebs.
1997. A review of statistical power analysis software. Bull. Ecol. Soc. A. 78(2):128–139.

Wonnacott, T. H., and R. J. Wonnacott.
1990. Introductory statistics for business and economics, 815 p. John Wiley & Sons, New York, NY.

Wyngaard, J. G., and M. I. Iorio.
1996. Status of the southern king crab (*Lithodes santolla*) fishery of the Beagle Channel, Argentina. *In* Proceedings of the international symposium on biology, management, and economics of crabs from high latitude habitats, Anchorage, Alaska, October 11–13, 1995, vol. 96-02, 25–39 p. Alaska Sea Grant College Program, Univ. Alaska, Anchorage, AK.

Zar, J. H.
1996. Biostatistical analysis, 663 p. Prentice-Hall, Inc., Upper Saddle River, NJ.

Zheng, J., T. J. Quinn II, T. J., and G. H. Kruse.
1993. Comparison and evaluation of threshold estimation methods for exploited fish populations. *In* Proceedings of the international symposium on mnagement strategies for exploited fish populations, Anchorage, Alaska, October 21–24, 1992 (G. H. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II, eds.), vol. 93-02, 267–289 p. Alaska Sea Grant College Program, Anchorage, AK.