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Abstract.—Low stock status of red king crabs *Paralithodes camtschaticus* in Bristol Bay prompted an industry initiative to reduce the minimum size limit for the commercial fishery from 165 mm in carapace width (CW) to 152 mm in CW. In terms of carapace length (CL), which is the metric used in data collection programs, this is equivalent to a reduction from 137 to 128 mm CL. The rationale was primarily to reduce potential nontarget handling mortality, which was suspected to contribute to the depressed stock status. Analysis of red king crab fishery observer data showed that the reduced size limit would initially increase catch rates of legals (under new size limit) by 10−41%, diminish total bycatch of nontarget red king crabs (sublegal and female crabs) by 9–33%, and reduce the fishing effort (pot lifts) needed to attain annual catch quotas by 2–27%. Yield-per-recruit analysis indicated that steady-state yield would decline 5–7% under the smaller size limit, assuming a 20% handling mortality rate. Size distributions of the catch would shift so that crabs of 128–136 mm CL would constitute 35% of the catch, yet the percentage of large males (>163 mm CL) in the spawning stock would barely increase from 6.1% to 8.2%. A population dynamics model revealed that there is a slightly higher probability of larger stock spawning biomass under the 128-mm-CL size limit than under the 137-mm-CL limit over a 50-year planning horizon. An economic break-even analysis showed that it takes 23 years for cumulative catch under the 128-mm-CL size limit to exceed cumulative catch under the 137-mm-CL size limit. At a 7% real interest rate, the reduced size limit takes 40 years to break even. Net benefits of the reduced size limit are larger and accrue more quickly if handling mortality rates are greater than 20%, whereas the reduced size limit never yields a positive economic benefit if handling mortality rates are 10% or less. The reduced size limit does not appear to be a cost-effective measure for red king crab resource conservation given likely values of handling mortality rates.

Red king crabs *Paralithodes camtschaticus* are widely distributed on both sides of the North Pacific from the Sea of Japan (Sato 1958) and British Columbia (Butler and Hart 1962) north through the Bering Sea to the Chukchi Sea (C. Lean, Alaska Department Fish and Game [ADFG], personal communication). These anomurans achieve maximum size (males) of 227 mm carapace length (CL; Powell and Nickerson 1965) and ages greater than 20 years (Matsuura and Takeshita 1990), although few crabs live longer than 15 years. After mating, fertilized eggs are incubated externally on the female's abdomen for nearly 1 year. Male crabs recruit to the Bristol Bay (eastern Bering Sea) fishery 7–12 years after hatching, depending on temper-

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ature (Stevens 1990). The fishery cannot legally retain females. The species supports some valuable yet volatile fisheries in the Gulf of Alaska, Aleutian Islands, and Bering Sea. In Bristol Bay in the eastern Bering Sea, a fishery developed in the early 1930s and peaked in 1980 with a catch of 59,000 metric tons (mt) worth US$115 million exvessel. Catches declined sharply in the early 1980s, and no fishing was permitted in 1983, 1994, and 1995 due to low stock size. Nevertheless, even with a short 4-d season in 1996, the fishery was lucrative; 3,800 mt were landed worth $34 million exvessel.

The rise and crash of many Alaska crab fisheries prompted a plea to reevaluate management strategies (e.g., Kruse 1993). Based on simulation studies (Zheng et al. 1997a, 1997b) the Alaska Board of Fisheries adopted in 1996 a more conservative harvest strategy to promote stock rebuilding and long-term optimal harvest of Bristol Bay red king crabs. Under the new strategy, a guideline harvest level (GHL; i.e., annual catch quota) is calculated by

$$\mathrm{GHL} = E \cdot N \cdot W_{\mathrm{ave}}, \qquad (1)$$

where E is annual exploitation rate, N is number of mature males ($\geq$120 mm CL) in the population estimated by length-based analysis (Zheng et al. 1995a, 1995b), and W_{ave} is average weight of legal male crabs. No fishery occurs ($E = 0$) when the stock is below thresholds of 8.4 million mature females and 6,600 mt of effective spawning biomass. Effective spawning biomass is the estimated biomass of mature females mated in a given year based on sex ratio and male size distribution (Zheng et al. 1995a, 1995b). When the stock is above threshold but below the rebuilding target level of 25,000 mt of effective spawning biomass, $E = 10\%$. When the stock is greater than or equal to 25,000 mt, $E = 15\%$ to optimize the tradeoff between long-term yield and variability in yield.

Although the harvest rate in equation (1) is applied to mature male crabs, only legal male crabs may be harvested and legal male harvest rate is capped at 50%. The minimum size limit for red king crabs in the Bristol Bay fishery is 165 mm (6.5 in) carapace width (CW). Carapace width is used for legal size determinations in the fishery and is measured as the straight-line distance across the carapace at a right angle to a line midway line between the eyes to the midpoint of the posterior portion of the carapace including the spines (ADFG 1997). Carapace length is the ''biological measurement'' defined as the distance from the posterior margin of the right-eye orbit of the carapace to the center of the posterior carapace margin (ADFG 1990). Because CL is used in all assessment, onboard observer, and dockside sampling programs, CL was used in all analyses reported here. Alternative size limits in CW were converted to CL by CL = 16.934 + 0.730 CW ($r^2 = 0.95$, $P < 0.001$, $N = 805$) for red king crabs collected from Bristol Bay during 1986 and 1987 (R. S. Otto, National Marine Fisheries Service, personal communication). The 165-mm-CW size limit corresponds to 137 mm CL.

The coupling of harvest rate and minimum size limit is critical to achieve management objectives pertaining to yield optimization and resource conservation. In Alaska, size limits for red king crabs were set based largely on market considerations (Donaldson and Donaldson 1992) and the ability to provide males at least one mating opportunity before harvest (Otto 1985).

Merits of alternative limits have been considered for more than 2 decades (e.g., Alverson 1980; Bibb and Matulich 1994). Interest in size-limit reduction to 128 mm CL (152 mm CW) stems from conservation concerns about bycatch mortality of discarded sublegal male crabs (Matulich and Bibb 1992; Reeves 1993; Thomson 1996). Proponents contend that a reduced size limit will shift harvest to smaller males, increase the number of larger and reproductively more prolific males, reduce bycatch mortality, promote more rapid stock rebuilding, increase catch per unit effort (CPUE), and reduce harvest operational costs.

Our goal was to analyze potential bioeconomic impacts of an industry proposal to reduce the size limit from 137 mm in CL (165 mm CW) to 128 mm in CL (152 mm CW), holding the number of harvested crabs constant. We analyzed the pros and cons of the reduced size limit with four related analyses. (1) Observer data from the red king crab fishery were analyzed to evaluate whether a reduced size limit will simply shift the bycatch problem to other components of the stock and to calculate empirically derived estimates of immediate changes in total bycatch, CPUE, GHL, and fishing season length. (2) A yield-per-recruit analysis was conducted to allow estimation of effects of size-limit reduction in terms of this classical steady-state solution to the size-limit problem and to facilitate direct comparison of our findings with previous analyses of this stock. (3) A simulation model of the Bristol Bay population was constructed with stock, environment, and fishery dynamics to estimate implications of size-limit reduction on catch and likelihood of future fishery closures over a 50-year planning horizon. (4) These simulation results were distilled into a break-even analysis to evaluate industry's proposed policy as an investment in conservation. Sensitivity of our models to uncertain handling mortality rates and discount rates were investigated.

Methods

Analysis of fishery observer data.—At-sea observers collected data from the Bristol Bay red king crab fishery during 1991–1993 and 1996; the fishery was not opened in 1994–1995 due to low abundance. All catcher–processors and at-sea processors carry fishery observers; catcher–processor catches were sampled when crab pots (typically 213 × 213 × 86 cm) were retrieved, whereas presorted deliveries from catcher-only vessels were sampled on those vessels. Crabs in observed pots were enumerated and identified to species, sex, size, shell condition, and other attributes.

If 128–136-mm-CL male red king crabs tend to be more closely associated with the bycatch of females or smaller males (<128 mm CL) than with the catch of larger (≥137 mm CL) males, then a reduced size limit may simply shift the bycatch problem to another segment of the population. To explore this, we calculated the correlation between catches of 128–136 mm CL male crabs with females and with smaller (<128 mm CL) and larger males (≥137 mm CL). Also, we estimated the magnitude of reduced bycatch and increased CPUE (catch per pot) as a result of the shift in definition of legal crabs. Crab CL (L in mm) was converted to weight (W in g; Balsiger 1974) with

$$W = 3.614 \cdot 10^{-4} \cdot L^{3.160}. \qquad (2)$$

Mean weight of legal crabs was estimated and GHL was calculated with equation (1) under the two size limits. Last, the number of fishing days needed to attain the GHL was calculated from estimates of daily fishing effort (number of pots fished) and CPUE (catch per pot).

Yield-per-recruit analysis.—A yield-per-recruit analysis examines the change in cohort biomass with age from growth and mortality tradeoffs (Beverton and Holt 1957; Ricker 1958). Yield is affected by the age of entry to the fishery and exploitation rate. Because red king crabs cannot be aged, we constructed a length-based cohort model to estimate yield per recruit. The initial number of crabs in the cohort was set equal to 1,000 crabs at relative age 0 and having an initial mean size of 105 mm CL and standard error of 6.0, which was consistent with Zheng et al. (1995a). These sizes correspond to crabs that are approximately two molt increments below legal size in Bristol Bay (Stevens 1990). This ''cohort'' comprises crabs of various ages depending on individual growth histories (Stevens 1990), so we kept track of relative, not absolute, cohort age.

We modeled growth identically to Zheng et al. (1995a, 1995b). Growth was separated into two components: growth increment (G) as a linear function of premolt size (L) measured in CL (mm),

$$G_L = 13.14 + 0.018L, \qquad (3)$$

and molting probability (P) as a logistic function of premolt size,

$$P_L = 1 - \frac{1}{1 + \alpha e^{-\beta L}}. \qquad (4)$$

Periods of slow (1980–1984, 1992–1993), medium (1985–1991), and fast growth (1972–1979) associated with shifts in molting probability occurred during the past 3 decades (Balsiger 1974; Zheng et al. 1995a). To explore the impacts of growth changes on yield, estimates of parameters α and β were set for periods of low (20,584.9 and 0.077), average (295,159.6 and 0.089), and high (358,930.1 and 0.082) molting probabilities for crabs of size 95–160 mm CL. Crab size measurements were converted to weight estimates with equation (2) for yield estimation.

Instantaneous natural mortality (M) of mature males was equated to a long-term weighted average value of 0.3 (Zheng et al. 1997b), corresponding to a 26% proportionate annual rate. Legal-sized males were assumed to be fully catchable, whereas sublegal-sized males were assumed to have 50% catchability based on observed bycatch rates in the directed fishery (Zheng et al. 1997a). Nonlegal male crabs must be returned to the sea, and an unknown number die from handling. We assumed a handling mortality rate of 20%, and examined the sensitivity of results to alternative rates between 0% and 50%. Zero and 50% mortalities are unrealistic, so we effectively bracketed the range of true values.

Simulation of stock rebuilding and fishery impacts.—As a contrast to the steady state yield-per-recruit analysis, we used a dynamic simulation model of stock rebuilding developed by Zheng et al. (1997b) to analyze the potential impacts of a size-limit reduction on the red king crab stock and the commercial fishery in Bristol Bay. Because average weight of landed legal crabs would decline under the reduced size limit, adoption of the proposal would lower the GHL, at least initially before conservation benefits accrue. Therefore, impacts of the proposed policy on stock rebuilding and fishery yield over time were of particular interest. Our only change to the model was to initialize the stock with data from 1996 rather than 1994.

In overview, we modeled both male (≥95 mm CL) and female (≥90 mm CL) components of the stock. Following Zheng et al. (1995a), stock–recruitment data were fitted with a Ricker curve that combined density-dependent stock effects with autocorrelated environmental effects seemingly associated with dynamics of the Aleutian Low pressure system (Tyler and Kruse 1996; Zheng and Kruse, in press). Spawning stock was estimated as effective spawning biomass. Male growth was modeled identically to our yield-per-recruit analysis, using parameters for weighted average growth during low, medium, and high molting periods. Female growth was modeled the same as males but with the sex-specific and stock-specific parameters reported in Zheng et al. (1995b). Instantaneous natural mortality for males was identical to that in the yield-per-recruit analysis, and for females it was set equal to 0.47 (i.e., 37% per annum). We assumed that groundfish trawls kill 200,000 red king crabs annually, the upper bound on crab bycatch set for the Bering Sea groundfish fisheries (NPFMC 1996). Handling mortality was treated identically to our yield-per-recruit analysis. Starting in 1996, we simulated the Bristol Bay red king crab stock and fishery under status quo (137 mm CL) and reduced (128 mm CL) size limits over a 50-year planning horizon under the current harvest strategy (equation 1). Each scenario was replicated 500 times to ensure relative stability of the summary statistics. We compared catch, probability of future fishery closure (i.e., years when the stock was below threshold), and probability distributions of future stock status with respect to the rebuilding target level (25,000 mt) under the two management alternatives.

Economic analysis.—The simulated catch trajectories were translated into financial streams that measure the direct economic benefits and costs of the policy proposal—i.e., the present value of harvest weight changes over time. This type of analysis treats the proposed size-limit reduction as an investment in conservation, which begs the question, ''When will the expected stream of benefits equal and then exceed the expected stream of costs?'' An economic break-even analysis was conducted to estimate how long it takes the crab industry to recoup its investment in conservation (reduced GHLs) before it benefits economically from higher yields of healthier stocks. The analysis compresses each 50-year catch trajectory into a single, cumulative dollar amount that removes the influence of time and interest from future dollar values. The break-even analysis calculates present value (PV) of ex-wholesale gross revenues from the 50-year harvest streams with and without the conservation policy. The lower size limit breaks even and begins to yield PV in excess of that under the current size limit when the net present value (NPV) is zero:

$$\mathrm{NPV} = \mathrm{PV}_{(128\ \mathrm{mm\ CL})} - \mathrm{PV}_{(137\ \mathrm{mm\ CL})} = 0. \quad (5)$$

The PV calculations are conditional on three parameters: ex-wholesale price, handling mortality, and interest rate. Average ex-wholesale price of processed red king crab is assumed to be $19.89/kg for both harvest trajectories; product recovery rate is 64% of live weight. Five handling mortality rates (0, 10, 20, 30, and 50%) were examined to reflect uncertainty of the estimates. Each mortality-conditioned PV estimate was then calculated with alternative real (i.e., inflation-adjusted) interest rates ranging from 0% to 7% (removal of inflation, 2.0–2.8% at the time of analysis, essentially holds wholesale crab prices constant over time). Although the expected real interest rate for short-term operating loans in the Bering Sea crab industry is 7% or less (about 9–10% nominal interest rate), lower rates were also considered to illustrate the sensitivity of reduced size-limit policy to more conservation-oriented interest rates.

A second economic implication involves altering the catch-by-size distribution over time. The reduced size limit initially will depress ex-wholesale prices (and thus, exvessel prices), followed by periods of rising and falling prices as the average weight per crab fluctuates with red king crab year-class strength. Precise incorporation of such price effects is not possible with available information. Wholesale price data do not exist for the currently sublegal (<137 mm CL) crabs and the influence of this smaller crab category on the price of larger crab size categories (so-called cross-price effects) are unknown (Matulich and Bibb 1992). Moreover, the future catch-by-size distribution depends on future changes in harvest policy and effectiveness of stock rebuilding, which is partly dependent on environmentally driven re-

TABLE 1.—Correlation coefficients (r) of catches of 128–136-mm-CL males with other male sizes (≥137 mm CL and <128 mm CL) and females from observed pots during the commercial fishery ($P < 0.05$*, $P < 0.01$**).

Year	N	Male size (mm CL) ≥137	<128	Females
1991	249	0.33**	0.72**	0.32**
1992	260	0.58**	0.60**	0.07
1993	532	0.64**	0.59**	0.08
1996	33	0.53**	0.38**	0.37*

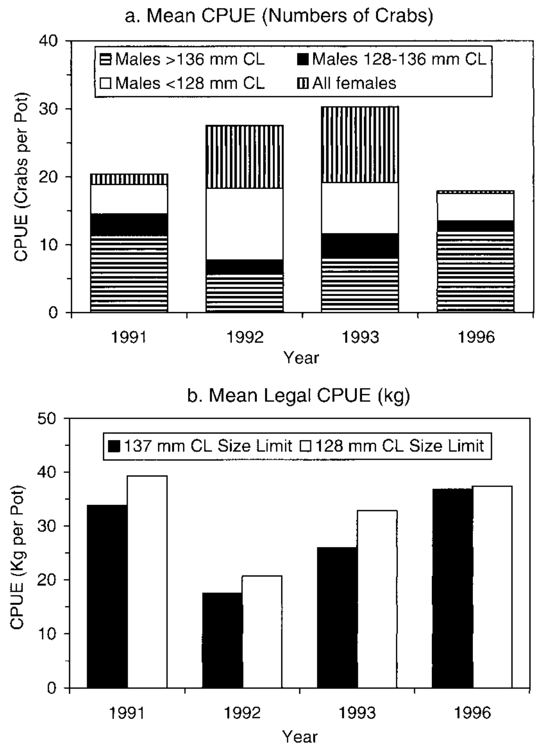

FIGURE 1.—Mean catch per unit effort (CPUE) in 1991–1996 as (a) numbers of males in three size-groups and all females and (b) total kilograms per pot of legal male crabs under the 137-mm-CL size limit and under the 128-mm-CL size limit; based on observed pot catches during the 1991–1996 commercial fishery in Bristol Bay.

cruitment cycles (Zheng and Kruse, in press). Regardless, some quantitative insight into this issue is gained by examining the NPV sensitivity to lower average prices. An ADFG cost-recovery fishery in 1995 provides additional qualitative insight into near-term revenue consequences of the lower size-limit policy. The participating processor accepted crabs of 128 mm CL or larger for the first delivery, but because of adverse revenue implications, field crews were asked to high-grade so that only crabs 147 mm CL or larger were landed during the second delivery.

The one remaining economic consideration concerns harvesting cost reductions due to higher CPUEs attending higher retention rates and subsequent stock rebuilding. Data do not exist to address this issue.

Results

Fishery Observer Data Analysis

During 1991, 1992, 1993, and 1996, observers were respectively deployed on 24, 17, 16, and 4 catcher-processor vessels and sampled 266, 280, 556, and 33 pots. Among pots that caught red king crabs, a statistically significant relationship was high ($P < 0.01$) between catches of 128–136 mm CL males and catches of smaller and larger males in all 4 years (Table 1). Correlations between 128- and 136-mm-CL males and females were significant ($P < 0.05$) in 2 of 4 years.

Legal (≥137 mm CL) males constituted 21–68% of all red king crabs caught during 1991–1996 (Figure 1a). If the size limit had been reduced to 128 mm CL, bycatch rates of all nonlegal crabs would have declined by 9–33% and catch rates of legal males would have increased by 10–41%. In terms of weight, catch rates would have increased to a lesser degree (2–27%) because of lower average weight of landed crabs under the smaller size limit (Figure 1b). These empirically derived estimates of catch and bycatch rates only reflect expected initial changes associated with a reduced size limit because they do not reflect cumulative effects on stock size composition over time.

A reduction in size limit would have reduced preseason GHL by 7–11% because of reduced mean weight of legal crabs: from 8,100 to 7,538 mt in 1991; 4,635 to 4,145 mt in 1992; 7,560 to 6,777 mt in 1993; and 2,250 to 2,070 mt in 1996. Mature male harvest rate was 20% during 1991–1993 and 10% in 1996, when harvest strategy was changed to equation (1) and our GHL estimates preserved these historical rates. From increased legal male CPUEs (Figure 1b), we estimated the percent reduction in fishing effort (number of pot lifts) needed to achieve the reduced GHL each year under the 128-mm-CL size limit: 16.3% in 1991, 18.4% in 1992, 26.6% in 1993, and 1.5% in 1996. Corresponding reductions in season length (rounded to 0.5 d) were from 7 to 6 d in 1991, 7 to 5.5 d in 1992, 9 to 7 d in 1993, and no change in the 4-d season in 1996.

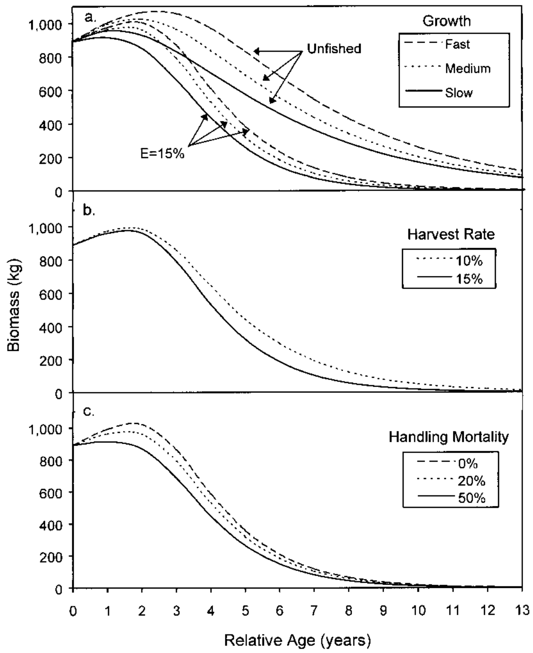

FIGURE 2.—Equilibrium cohort biomass and relative age for Bristol Bay red king crabs under scenarios of (a) slow, medium, and fast growth with no harvest and with a 15% mature male harvest rate provided under a 137-mm-CL size limit and assuming 20% handling mortality; (b) medium growth with 10% and 15% mature male harvest rates provided under a 137-mm-CL size limit and assuming 20% handling mortality; and (c) medium growth with a 15% mature male harvest rate provided under a 137-mm-CL size limit and assuming handling mortality rates of 0, 20, and 50%. Crabs with a mean size of 105 mm CL are relative age 0.

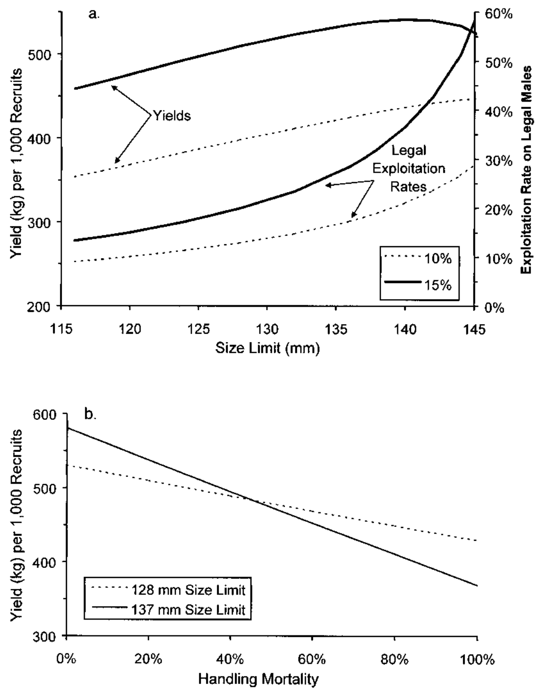

FIGURE 3.—Yield (kg) per 1,000 recruits for Bristol Bay red king crabs based on (a) 10% and 15% mature male harvest rates under alternative size limits (115–145 mm CL) and assuming 20% handling mortality, and (b) 15% mature male harvest rate under two size limits (128 and 137 mm CL) and assuming 0–50% handling mortality.

Yield Per Recruit Analysis

Cohort biomass at a given relative age declines as growth rate decreases and as exploitation rate or handling mortality increases (Figure 2). Faster growth shifts age of maximum biomass to older ages. In an unfished situation, biomass of an initial cohort of 1,000 crabs peaks at 1,063 kg at relative age 2 during years of fast growth, and 954 kg at relative age 1 during periods of slow growth (Figure 2a). Under medium growth, cohort biomass is maximized at 1,024 kg for relative age 2. Prosecution of a fishery reduces cohort biomass and shifts peak biomass to younger ages (Figure 2a). Cohort biomass is greatest at relative age 2 with fast growth and greatest at relative age 1 with medium and slow growth, under the current size limit and 15% mature-male harvest rate assuming 20% handling mortality. Compared with 15%, a 10% harvest rate provides for greater cohort biomass at older ages (Figure 2b). Not surprisingly, as handling mortality increases, cohort biomass declines (Figure 2c). Under the current size limit and the 15% mature male harvest rate, cohort biomass is maximized at relative age 2 for handling mortality rates less than 20% and at relative age 1 for higher handling mortality rates.

Assuming a 20% handling mortality rate, a reduction in size limit from 137 to 128 mm CL would slightly decrease yield per recruit by 7% under the 10% mature-male harvest rate and by 5% under the 15% mature-male harvest rate (Figure 3a). Over the range of size limits examined, larger yields per recruit are obtained from larger minimum size limits. Handling mortality reduces yield per recruit (Figure 3b); the greater the mortality, the greater the loss of yield. However, for probable values of handling mortality rate (≤45%), the current size limit results in higher yields than the reduced size limit.

Yield-per-recruit analysis allowed us to examine the degree to which a reduced size limit shifts the

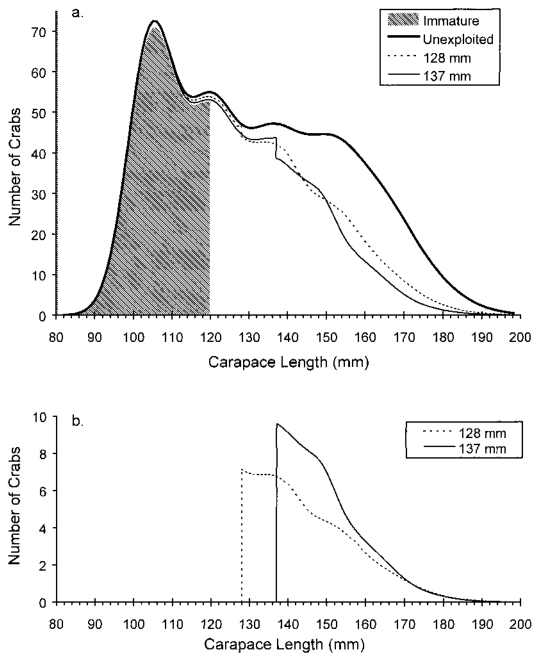

FIGURE 4.—Size structure of the (a) equilibrium population and (b) catch for Bristol Bay red king crabs under two different size limits (128 and 137 mm CL) with a mature male harvest rate of 15% and sublegal handling mortality of 20%.

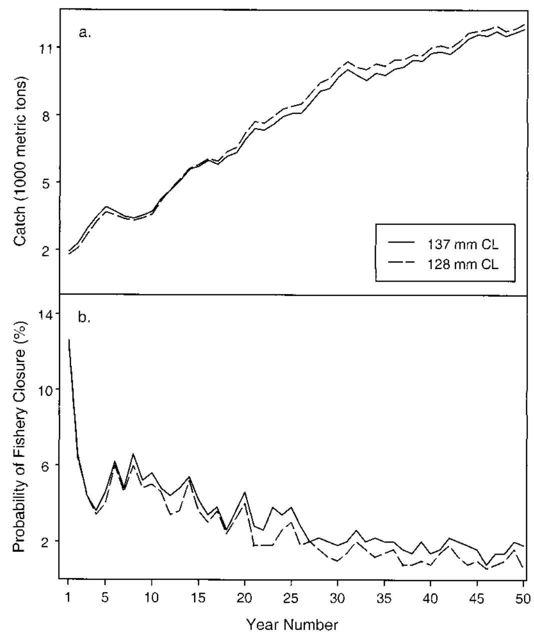

FIGURE 5.—Simulated (a) annual mean catch and (b) probability of fishery closure for the Bristol Bay red king crab fishery over 50 years under the current 137-mm-CL and proposed 128-mm-CL size limits and assuming 20% handling mortality rate. Year 0 is 1996.

population size distribution to larger male crabs. Because harvest rate is applied to the number of mature males, legal male exploitation rate increases with higher size limits because the catch is taken from a smaller fraction of the male population (Figure 3a). For the 128 mm CL size limit, harvest is spread over a larger segment of the stock, shifting the average size of crabs in the equilibrium catch from 149.7 to 144.5 mm CL (Figure 4b). Crabs greater than or equal to 137 mm CL decline from 100% to 65% of the catch, replaced by males 128–136 mm in CL. However, due to natural mortality, large (>163 mm CL) males, which predominate collections of mating pairs off Kodiak Island (Schmidt and Pengilly 1990), only increase from 6.1% to 8.2% in the equilibrium population (Figure 4a).

Simulation of Stock Rebuilding and Fishery Impacts

Under the base scenario of 20% handling mortality rate, annual mean commercial catch is slightly higher for the 137-mm-CL than for the 128-mm-CL size limit during the first 11 years (Figure 5). After year 16, annual mean catch for the smaller size limit is 125–450 mt or about 1% to 5% higher than that under the status quo. It takes 23 years for cumulative catch under the 128-mm limit to exceed catch under the 137-mm limit. Probability of fishery closure is very similar for the two size limits during the first 5 years, but subsequently there is a slightly higher chance for fishery closure under the current size limit (Figure 5). A close examination of the probability distribution of effective spawning biomass, with respect to target rebuilding level, shows that there is a slightly higher probability of higher biomass under the 128-mm limit than under the 137-mm limit after 30 and 50 years (Figure 6).

Our results are sensitive to handling mortality. With no handling mortality, the probability of fishery closure is identical under the two size limits, but the fishery would be closed much less often under the reduced size limit than under the current size limit when handling mortality rate increases above 20% (Figure 7). Annual mean catch is slightly higher under the status quo than under the reduced size limit when handling mortality rate is 0–10% during each of the 50 years (Figure 8). However, with handling mortality rates greater than or equal to 20%, annual mean catch is much

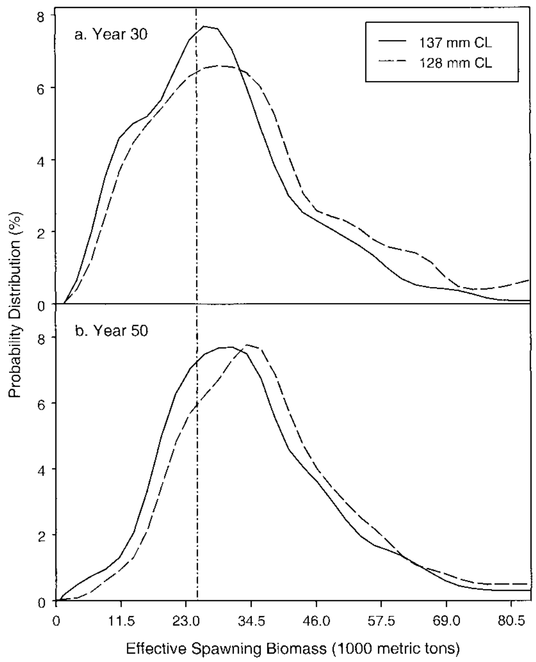

FIGURE 6.—Probability distributions of effective spawning biomass of Bristol Bay red king crabs after (a) 30 years and (b) 50 years (year 0 is 1996) for the 137-mm-CL and 128-mm-CL size limits. The vertical line indicates the target level of 25,000 metric tons of effective spawning biomass.

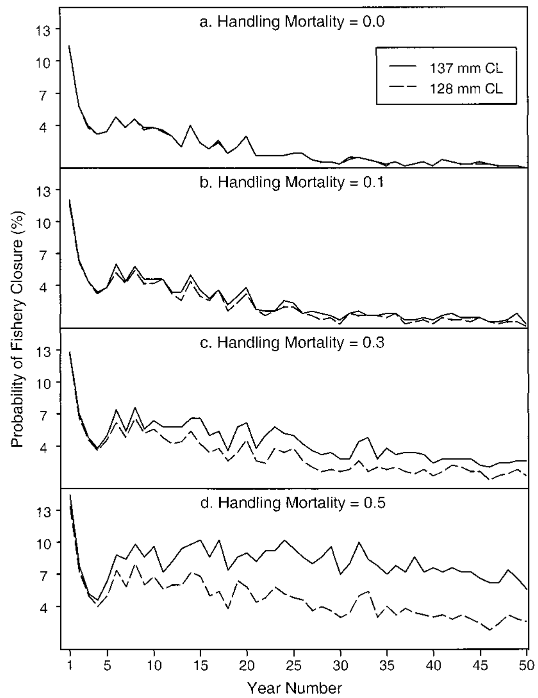

FIGURE 7.—Probability of fishery closure for Bristol Bay red king crabs over 50 years (year 0 is 1996) under handling mortalities of (a) 0, (b) 10, (c) 30, and (d) 50% and under the 137-mm-CL and 128-mm-CL size limits.

higher for the 128-mm-CL size limit than for the 137-mm limit after 15–20 years.

Economic Analysis

Two generalizations can be drawn from the break-even analysis (Figure 9). First, larger interest rates make future benefits less valuable because they require a longer time to break even. Second, higher handling mortalities yield greater economic benefits from the reduced size limit. The reduced size limit never pays if the handling mortality is 10% or less, regardless of interest rate. At the policy-relevant 7% real interest rate, the conservation policy takes 40 years to break even, assuming that handling mortality is 20% and 19 years if the handling mortality is 30%. Even at the unrealistically high 50% handling mortality rate, it would take 13 years for the industry to realize any positive net economic benefit. This long payoff period raises a question about industry motivation. If the industry's conservation interest is altruism or intergenerational wealth transfer, the appropriate interest rate is 0% (i.e., after 50 years $1 is equivalent to $1 today). The reduced size limit still takes 22, 14, or 10 years to break-even under 20, 30 and 50% handling mortalities, respectively. Thus, the 128-mm limit involves a protracted payback period even in the absence of any positive time value of money.

Although we did not simulate complex changes in catch-by-size distribution and prices due to a change in the size limit, we did attempt to gain insight into the economic consequences of lowering the size distribution from the ADFG cost-recovery fishery in 1995. Mean weight of live red king crabs in deliveries under the 128-mm-CL and 147-mm-CL size limits were 2.4 kg and 3.1 kg, respectively. Processed crabs were graded into five size categories (Figure 10). The finished product grading system measures weight in grams of a cluster (i.e., three walking legs and a claw from one side of a crab's body), where M = 300−499 g and L = 500−699 g, 2 L = 700−899 g, 3 L = 900−1,099 g, 4 L = 1,100–1,299 g, and 5 L is 1,300 g and greater. This system is commonly used in the Japanese market, which is the primary market for Bristol Bay red king crabs.

The 128-mm limit resulted in a substantially smaller size distribution of processed product than

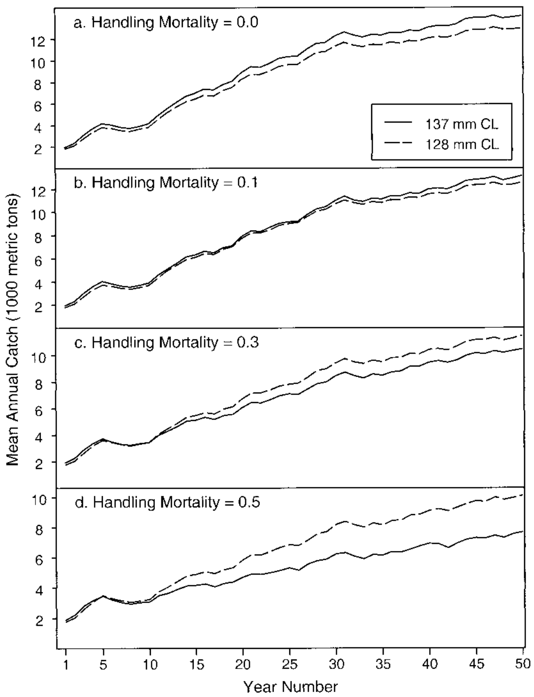

FIGURE 8.—Estimated mean annual catch of Bristol Bay red king crabs over 50 years (year 0 is 1996) under handling mortalities of (a) 0, (b) 10, (c) 30, and (d) 50% and under the 137-mm-CL and 128-mm-CL size limits.

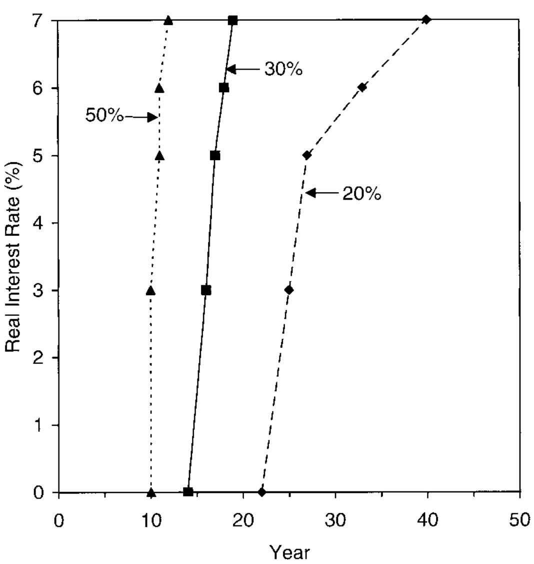

FIGURE 9.—Break-even analysis for the Bristol Bay red king crab fishery under 50, 30, and 20% handling mortalities. Plotted are the number of years needed for the payoffs to equal the cost of the investment, i.e., $PV_{(128\text{ mm CL})} - PV_{(137\text{ mm CL})} = 0$. Benefits never exceed costs when handling mortality equals 0 and 10%.

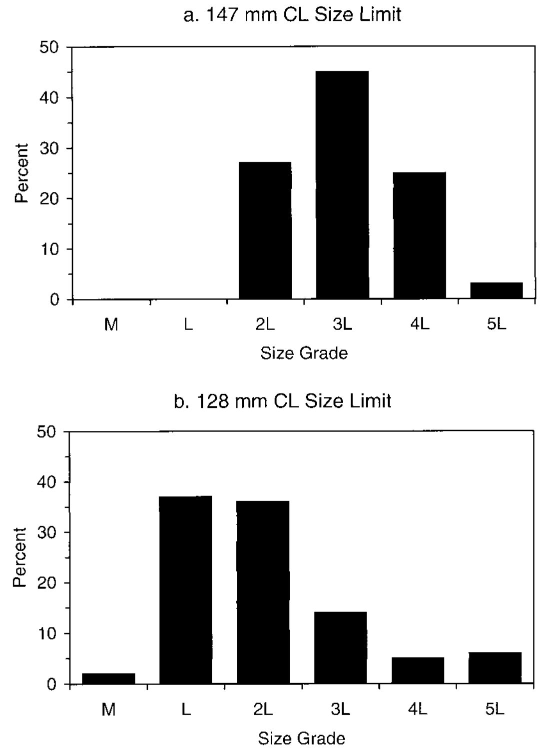

FIGURE 10.—Size-grade distribution (M = 300−499 g, L = 500−699 g, 2 L = 700−899 g, 3 L = 900−1,099 g, 4 L = 1,100–1,299 g, and 5 L is 1,300 g and greater) of processed red king crabs from two deliveries made during the ADFG cost-recovery fishery in Bristol Bay during 1995: (a) a first delivery in which a 128-mm-CL size limit applied, and (b) a second delivery when a 147-mm-CL size limit applied.

the 147-mm limit (Figure 10). Average cluster weight decreased more than a full grade from more than 3 L to 2 L. Price differentials among size grades differ from year-to-year depending upon market conditions. Generalizations from the particular market circumstances of the ADFG cost-recovery fishery should be avoided. Nevertheless, it is instructive to consider how reduced catch-by-size might affect the magnitude of loss in just the first year under the two size limits. The industry would incur an expected first year loss of $1.7 million. On the one hand, high grading for crabs larger than 147 mm CL (rather then 137 mm CL) overstates the first-year loss estimate associated with the proposed size-limit reduction. On the other hand, this estimate is understated because it only reflects the diminished GHL due to lower average red king crab weight in equation (1) rather than any price drop. First-year losses would more than double to $4.0 million if the smaller size distribution caused the average ex-wholesale price per pound to decline $1 to $17.68/kg. If average price fell to $15.47/kg, the industry would experience a $6.4 million loss in the first year.

Discussion

Previous scientific recommendations on minimum size limits for the Bristol Bay red king crab fishery were based primarily on yield-per-recruit analyses. This advice has been conflicting and ambiguous. A chronology of published recommended size limits in terms of millimeters CL (mm CW) is 158 (193) by Hirschhorn (1966), 151 (183) by Hirschhorn (1966) reanalyzed by Balsiger (1974), 150–155 (183–191) by Greenough (1972), 136 (163) by Balsiger (1974), 120–133 (142–159) by Alverson (1980), 114 (133) by Reeves and Marasco (1980), and 110 (127) by Reeves (1988). Discrepancies are largely due to differences in growth and mortality estimates. For instance, Balsiger (1974) estimated growth of recaptured crabs tagged during 1954–1961 and 1966–1969, whereas Greenough (1972) used Weber and Miyahara's (1962) growth estimates from tagging during 1955–1957. Because large crabs tagged in 1955–1957 grew faster than in other years, Greenough estimated a larger optimal size than Balsiger. Growth slowed in the 1980s and 1990s, so our estimates of long-term mean growth are generally less than those used in studies conducted in the 1960s and 1970s.

Compared with recent studies, pre-1980 investigations estimated lower M from mark–recapture studies, and correspondingly, larger size limits were recommended. Studies in the 1980s were based on an age–length key applied to survey size-frequency data. Unfortunately, large growth variability caused significant errors in resultant age estimates from this method. Indeed, 50% of Reeves' (1988) age-specific annual M estimates were less than 0.01 and were deleted as being too low, causing the average of the remaining values to be a biased estimator of mean population M. Our value (0.3), based on length-based analysis of long-term survey data over 1972–1993, is intermediate to published values (Zheng et al. 1995a). Instantaneous natural mortality increased 4–5 fold during 1980–1984 (Reeves 1988; Zheng et al. 1995a), but we held M constant because we analyzed long-term harvest policy and because we cannot rule out that high M in the early 1980s was fishing related. As a result of these combined growth and mortality effects, our analysis indicates that a size-limit reduction would diminish yield per recruit for this fishery.

Our simulation model of stock rebuilding provides a somewhat different view of expected yields over time under the two management alternatives. Small red king crabs conserved by reduced handling mortality eventually accumulate as larger standing stocks generating higher average recruitment, a biological feedback not considered by yield-per-recruit analysis. Because of the relatively slow growth and late maturity of red king crabs, the industry would have to wait more than 2 decades for the reduced size limit (at 20% handling mortality rate) to yield cumulative catches that exceed those under the current size limit. This protracted biological payback period raises questions concerning length of the economic payback for what is ostensibly an investment in conservation.

A proper bioeconomic analysis would estimate the net present value of economic surpluses (revenues in excess of variable costs) under the two management alternatives. Instead, this analysis focused on a partial economic metric—change in ex-wholesale gross income—because cost data for the fleet and processors are not available under the current policy, let alone the proposed policy. Nevertheless, qualitative insights are possible, as are insights concerning potential policy bias.

The most notable economic effect of the reduced size limit is that it takes considerably longer, if ever, to provide a positive economic return than to provide for increased cumulative catches. An ancillary increase in harvesting efficiency (lower production costs) due to higher CPUE should at least partially offset diminished yields during the rebuilding phase. However, higher CPUE and lower GHLs may come at another cost. Improved harvesting efficiency may jeopardize the ability to manage this overcapitalized fishery in years of very low abundance and short fishing seasons (e.g., <4 d). All other things equal, a reduced size limit will result in an even shorter season. When inseason data are inadequate to close the fishery without exceeding the GHL, fishery managers have little recourse but to err in favor of stock protection by not opening the fishery at all. Such increases in the probability of fishery closures would lengthen the economic payback period under the reduced size limit. Moreover, a size-limit reduction will decrease the size-by-grade distribution, which in turn will lower prices and, thus, decrease gross receipts over some initial period of time. This unquantifiable effect exaggerates the aforementioned NPV implications. Anecdotal information indicates that the size distribution of Russian red king crabs is decreasing, and high grading has all but eliminated the largest size grades. As a result, prices for medium, and small size grades have reportedly softened. In summary, it appears that the economic ramifications of the size limit reduction would be deleterious to the financial well being of the Bering Sea red king crab industry.

Of course, catch and economic benefits are not the only grounds on which management decisions are made. The Magnuson–Stevens Fishery Conservation and Management Act of 1996 requires fishery management plans to implement rebuilding plans for overfished stocks and to include measures that minimize bycatch and mortality of unavoidable bycatch (NMFS 1996). Although Bristol Bay red king crabs are not classified as overfished, depressed stock levels persisted during the mid-1980s to mid-1990s. A moderately high 1990 year-class nudged the spawning stock over target levels in 1998 (Zheng et al. 1998), but long-term stock rebuilding remains an important fishery management goal. Recently, the Bering Sea king crab fishery was identified to have the second highest discard ratio (number discarded per number landed) of all fisheries worldwide (Alverson et al. 1994). Indeed, we estimated that 32–79% of king crabs caught in the Bristol Bay fishery were discarded in 1991–1996 because of size and sex restrictions. The benefit of bycatch reduction under the proposed smaller size limit, however, is diminished by the fact that females are illegal under both management alternatives.

The conservation benefits of reduced discards depend on handling mortality rates. Lethal and sublethal effects of handling on king crabs during commercial fisheries have not been completely investigated (Kruse 1993), but 10–20% mortality seems plausible. Handling does not inflict significant mortality under laboratory conditions when crabs are promptly returned to the water with care (Zhou and Shirley 1995, 1996). Also, low mortality (deadloss) rates are typical of crabs held in seawater tanks of fishing vessels for several days before delivery to processing plants. However, mortality estimates are not available for crabs returned to the sea during commercial fisheries. Exposure of red king crabs to extremely cold winter air temperatures increases mortality and reduces vigor and growth of the survivors (Carls and O'Clair 1990). Studies on the added deleterious cooling effects of winter wind are in progress. Fish and amphipod (*Anonyx* spp.) predation on injured crabs discarded during commercial fisheries are suspected but uncertain sources of handling-related mortality. Additional laboratory and field studies are needed to fully resolve the potential role of handling mortality on red king crab stocks.

The stock-recruit relationship used in our dynamic simulation model was based on a relationship between male size and average number of females mated per male. Small mature males (120–124 mm CL) mate with one female, and large males (>160 mm CL) mate with three females, which was determined in laboratory studies by Paul and Paul (1990, 1997). However, gains in male reproductive potential from the reduced size limit that are associated with a shift in catch distribution to smaller sizes appear to be very minor, partly because accumulated natural mortality of large, old red king crabs diminished the savings. Moreover, males were seldom limiting to reproduction, even under the current harvest strategy, which was designed to promote stock rebuilding. Admittedly, if unattended molting females experience increased predation or cannibalism, then the importance of mature males on population dynamics may be underestimated.

There may be other less costly management alternatives than reduced size limit to promote bycatch reduction and stock rebuilding. New gear designs are leading options. Zhou and Shirley (1997) designed a pot that in laboratory experiments reduced the catch probability of females and sublegal males by more than 60% while increasing the catch probability of legal males by more than 25%. Although the new pot did not perform to expectations under higher crab densities experienced during initial field trials in Bristol Bay (Zhou and Kruse, Alaska Department of Fish and Game, unpublished data), adjustments may result in a pot that significantly reduces bycatch in the fishery. A large (22.86 cm) stretch-mesh panel, required in crab pots starting in 1996, shows promise. The percentage of nonlegal red king crabs in observed pots during recent fisheries declined from a mean of 64.5% during 1991–1994 to 31.8% in 1996. (However, due to few participating catcher–processors and a short season, the sample size in 1996 was only 9.5% of mean sample size during 1991–1994, so definitive conclusions of the effectiveness of the large mesh are premature.) In addition to reducing total bycatch, handling mortality rate should be minimized. Improved onboard sorting procedures and educational programs may improve crab survival. Adverse effects of winter weather on discarded crabs are a lingering conservation concern. Pending the outcome of ongoing investigations on cold wind chill effects, season adjustments may be a cost-effective way to reduce mortality rates of discarded crabs.

Should the size limit for the Bristol Bay red king crab fishery be reduced from 137 to 128 mm CL? Proponents are generally correct in many of their contentions about the reduced size limit. Most notably, bycatch would decline, CPUE would increase, and spawning biomass and commercial catches would increase slightly over a 50-year period. On the other hand, a large industry investment in conservation would be recouped over a very protracted pay-back period. Further, when abundance and GHLs are low, higher catch rates under the 128-mm-CL size limit increase the likelihood that stocks would be overharvested or that the fishing seasons would be foregone due to management concerns about exceeding prescribed limits. As a conservation measure, the reduced size limit has merits, but examination of the full suite of tradeoffs conducted in this integrated bioeconomic analysis leads us to recommend no change in minimum size limit for the Bristol Bay red king crab fishery. In addition to maintaining the current rebuilding plan with its schedule of conservative harvest rates, other more cost-effective measures should be explored to reduce total bycatch and lower handling mortality rates to accomplish long-term crab resource conservation objectives.

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