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Rebuilding Probabilities Under Alternative Management Strategies for Eastern Bering Sea Tanner Crabs

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ABSTRACT: Because of its depressed status the eastern Bering Sea Tanner crab *Chionoecetes bairdi* stock was deemed overfished in March 1999. This determination necessitated the development of a rebuilding plan. We estimated rebuilding times and rebuilding probabilities using a length-based model and computer simulations under 3 alternative rebuilding strategies for this stock: (1) a complete closure of the directed Tanner crab fishery and a maximum constraint on other fisheries, (2) no directed fishing mortality other than unavoidable bycatch mortality, and (3) a new harvest strategy for the directed Tanner crab fishery with the same bycatch constraints for other fisheries as strategy 2. Rebuilding times were estimated as 7 years for ≥50% probability and 20 years for ≥90% probability for strategy 1, 8 and 27 years for strategy 2, and 10 and 30 years for strategy 3. Distributions of total mature biomass were skewed; the mean biomass was much larger than the median value. The recruitment dynamic affected rebuilding time periods, probabilities of fishery closure, and mean annual yields. Estimated rebuilding times with a ≥50% probability ranged from 4 to >35 years depending on different assumptions on recruitment. Because the history of stock assessments is short (25 years) relative to the periodicity of recruitment cycles (13–14 years), additional years of data are needed to resolve alternative recruitment models and to determine whether statistical relationships with oceanographic conditions can predict future Tanner crab recruitment success.

INTRODUCTION

Tanner crabs *Chionoecetes bairdi* in the eastern Bering Sea have supported an important commercial fishery. Landings peaked at 31,300 metric tons in 1978, and annual exvessel values averaged US$46 million during 1990–1993. Landings dropped sharply after 1993, and the fishery has been closed since 1997 due to the depressed stock. In March 1999 the stock was deemed overfished by the U.S. Secretary of Commerce because mature biomass fell below one-half of the long-term average value that is assumed to produce maximum sustainable yield (MSY; NPFMC 1998).

When a stock is overfished the Magnuson–Stevens Fishery Conservation and Management Act (§304, 16 U.S.C. §1801) requires a rebuilding plan to be developed within one year (NMFS 1996). The rebuilding plan must specify a time period for stock rebuilding, and rebuilding probabilities must be estimated. Factors affecting the length of the rebuilding period and rebuilding probabilities include stock status and biology, interactions with other ecosystem components, and the needs of fishing communities. The lower time limit (T_{min}) for rebuilding is defined as the amount of time that would be required for rebuilding if directed fishing mortality were eliminated entirely. If T_{min} is <10 years the target rebuilding time (T_{target}) may be adjusted upward to 10 years if warranted to accommodate the needs of fishing communities. If T_{min} is ≥10 years T_{target} may be adjusted upward to accommodate the needs of fishing communities within other constraints. The T_{target} must not exceed the expected rebuilding time in the absence of fishing, plus the number of years corresponding to one mean generation time.

Tanner crabs in the eastern Bering Sea are concentrated in Bristol Bay and near the Pribilof Islands (Stevens et al. 1998). Approximately 75% of female biomass >79 mm carapace width (CW) and mature male (>112 mm CW) abundance, and 82% of legal male (i.e., commercially harvestable males ≥138 mm CW) abundance have historically occurred in Bristol Bay (Zheng and Kruse 1999a). Tanner crabs in Bristol

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Bay and near the Pribilof Islands differ genetically (Merkouris et al. 1998) and in size at maturity in some years. Annual survey measurement errors also differ between these 2 areas. Our modeling efforts to date have focused on Bristol Bay Tanner crabs (Zheng and Kruse 1998, 1999a, 1999b). Here, we extended our efforts by coupling a size-based population model (Zheng et al. 1998) and stock–recruitment relationships (Zheng and Kruse 1998) for Tanner crabs in Bristol Bay to form a computer simulation model to estimate rebuilding times and probabilities under alternative rebuilding strategies for this stock. Because Tanner crabs are not separated into Bristol Bay and Pribilof Islands stocks for management purposes, we applied the results to Tanner crabs throughout the eastern Bering Sea.

METHODS

Given the cyclic nature of Tanner crab recruitment with periods of 13–14 years (Zheng and Kruse 1998), it is difficult for the stock to remain at or above the mature biomass level that produces MSY (B_{msy}). Even in the absence of fishing, we estimated this stock would be classified as overfished 9% of the time (Zheng and Kruse 1999b). Based on its recruitment dynamics, we considered the stock to be rebuilt when the biomass exceeded B_{msy} in 2 consecutive years. This definition reduces the chance of erroneously determining, due to survey measurement errors or the occurrence of a single strong year class, that the stock is rebuilt.

Details of the length-based model and stock–recruitment models were described by Zheng et al. (1998) and Zheng and Kruse (1998, 1999b). Common features of the simulations for all scenarios and strategies in this study are:

- The model was initialized with population data for 1998.
- Measurement errors were assumed to be lognormally distributed with a standard deviation of 0.2 and mean of zero. The measurement errors were applied to the initial (1998) abundance and future biomasses and abundances used to set catch quotas.
- For each strategy we simulated the population and fishery for 35 years with 2,000 replicates. The rebuilding probabilities (the proportion of replicates being rebuilt), probabilities of fishery closure (the proportion of replicate-years with fishery closure during a given period), frequency distributions of total mature biomass from the simulations, and mean yields were compared for 3 rebuilding strategies. The fishery management plan defines B_{msy} for Tanner crabs in the entire eastern Bering Sea (NPFMC 1998), whereas our population model addresses just Bristol Bay. Based on the survey data in the Bristol Bay and Pribilof Islands areas from 1983 to 1997, we approximated the equivalent B_{msy} for Bristol Bay Tanner crabs as 53,200 metric tons of total mature male and female biomass.
- Recruitment R_t was modeled by an autocorrelated Ricker stock–recruitment model:

  $$R_t = S_{t-k}\, e^{\alpha-\beta S_{t-k} + \upsilon_t},$$

  where t represents year, S_{t-k} is the effective reproductive (spawning) biomass in year t-k, k is time lag from mating to recruitment to the size-based model, α and β are constants, and $\upsilon_t = \delta_t + \varphi\upsilon_{t-1}$ is environmental noise, assuming $\delta_t \rightarrow N(0,\sigma^2)$. Effective reproductive biomass was defined as the biomass of females >79 mm CW which can be mated by mature males (Zheng and Kruse 1998). The parameter values were estimated as $\alpha = 2.0402$, $\beta = 0.0563$, $\varphi = 0.73$, $\sigma = 0.86$, and $k = 8$ (Zheng and Kruse 1998). The component of normally distributed noise ($N(0,\sigma^2)$) was truncated at the 2.5% and 97.5% limits to prevent unreasonably large or small recruitment.
- The handling mortality rate of captured but discarded females and sublegal males was assumed to be 20% for the crab fishery. This rate falls between low rates from a study that attempted to emulate physical handling during fishing (MacIntosh et al. 1996) and high rates from a laboratory study that measured mortality of crabs exposed to extremely cold air temperatures common during winter fisheries (Carls and O'Clair 1995).

Three rebuilding strategies were applied during simulated rebuilding periods for comparison.

Strategy 1

No fishing mortality was allowed. The annual natural mortality rate, uncontaminated by any fishery-related effects, was assumed to be 26% ($M = 0.3$) for males and 27% ($M = 0.32$) for females. This strategy is equivalent to a complete closure of the directed Tanner crab fishery and a maximum constraint on bycatch in other fisheries. The current MSY and minimum stock size threshold (MSST) were estimated with $M = 0.3$.

Strategy 2

The directed Tanner crab fishery was closed. This strategy approximates no directed fishing mortality other than limited bycatch mortality. The annual natural mortality rate was assumed to be 33% ($M = 0.4$) for males and 35% ($M = 0.43$) for females to include some fishery-related sources of mortality that have not been explicitly identified and separated (Zheng and Kruse 1999b). Bycatch mortality from all non-pot fisheries was simulated separately from natural mortality. Bycatch from groundfish and scallop fisheries was set according to the current regulations that define prohibited species caps as modeled by Zheng and Kruse (1999b), and the handling mortality rate was assumed to be 80% for the groundfish fisheries and 40% for the scallop fishery (NPFMC 1996).

Strategy 3

A new harvest strategy approved by the Alaska Board of Fisheries in March 1999 for the directed Tanner crab fishery (Zheng and Kruse 1999a) was used, and bycatch constraints and natural mortality were the same as strategy 2. This strategy allowed the directed Tanner crab fishery to occur under the new harvest strategy and all other crab fisheries to occur under the current regulations. The new harvest strategy includes 4 components:

- Directed mature male harvest rates: 0 when the biomass of females (FB) >79 mm CW is <9,525 metric tons (21 million lb), 10% of molting mature males (100% of new-shell and 15% of old-shell males >112 mm CW) when FB ≥ 9,525 and <20,412 metric tons (45 million lb), and 20% of molting mature males when FB ≥ 20,412 metric tons (Zheng and Kruse 1999a)
- A 50% cap on the harvest rate for exploitable legal crabs (100% of new-shell and 32% of old-shell males >137 mm CW [5.5 in])
- A minimum guideline harvest level (GHL) of 1,814 metric tons (4 million lb)
- A 50% reduction of GHL when the fishery is reopened after having been closed in the preceding season due to FB <9,525 metric tons.

During simulations these biomass and GHL benchmarks established for eastern Bering Sea Tanner crabs were multiplied by 0.75 to approximate the levels for Bristol Bay only. For strategy 1 or 2, once the simulated population was rebuilt, strategy 3 replaced it for the remaining duration of the simulation. That is, strategy 3 was used during all non-rebuilding periods.

Sensitivities of rebuilding probability and rebuilding-period length to recruitment dynamics and handling mortality were also examined through computer simulations. As an alternative to the autocorrelated stock–recruitment model, a cyclic stock–recruitment model was specified with the same values of α and β as the autocorrelated model, but with an error term $\upsilon_t = A \sin(2\pi t/P) + \delta_t$ where A is period amplitude, P is period length, t represents years, and $\delta_t \rightarrow N(0,\sigma^2)$. Parameter values were estimated as $A = 1.268$, $P = 13$ years, and $\sigma = 0.46$ (Zheng and Kruse 1998). For sensitivity analyses estimated autocorrelated and cyclic models were considered to be base models, and only one parameter value was changed for each scenario. Six scenarios were compared for the autocorrelated model: base model, depensatory model, $\varphi = 0.4$ and 0.95, and handling mortality rate = 0.0 and 0.5. Five scenarios were compared for the cyclic model: base model, $A = 0.75$ and 1.75, and $P = 8$ and 21 years. The values used in these scenarios were within the likely ranges of the parameters. Recruitment was multiplied by an empirical constant in each scenario to ensure the expected long-term mean recruitment levels for all scenarios were approximately equal. The depensatory model was the same as the autocorrelated model except that the deterministic component of recruitment declined exponentially with stock size, $R_t = \kappa S_{t-k}^{\theta}$, when S_{t-k} was 6,395 metric tons or less, $\kappa = 0.203$, and $\theta = 2.803$ (Zheng and Kruse 1998). A range of A values from 6 to 30 years with intervals of 2 years, and a range of P values from 0.5 to 2.5 with intervals of 0.25 were used in simulations to construct contour plots of rebuilding times.

The default definition of generation time of Restrepo et al. (1998, p. 37) was used to estimate generation time, which is equal to the biomass-weighted average age of mature females. For this calculation body size was converted to age with a relationship developed by Donaldson et al. (1981), and a natural mortality of 0.32 for females was assumed.

RESULTS

Estimated rebuilding probabilities increased asymptotically over time (Figure 1). For all 3 strategies zero probability was generally estimated during the first 2 years. Rebuilding times were estimated at 7 years for ≥50% probability and 20 years for ≥90% probability for strategy 1, 8 and 27 years for strategy 2, and 10 and 30 years for strategy 3. Distributions of total mature biomass were skewed, and the long tail for large biomasses caused mean biomass to be much larger than the median value (Figure 2).

Female Tanner crabs mature at approximately 6–7 years (7–8 years for males) from egg fertilization and may reproduce for 5 years. An estimate of mean generation time is 8 years. Because some bycatch mortality is unavoidable, we used strategy 2 to establish a realistic T_{min}. Based on a 50% rebuilding probability and the autocorrelated stock–recruitment model, T_{min} was 8 years, and the upper limit (T_{max}) should be 10 years (Restrepo et al. 1998). Because T_{min} was <10 years it was not necessary to add generation time to the rebuilding period. If a 90% rebuilding probability was used, T_{min} was 27 years and T_{max} was equal to T_{min} plus the mean generation time, or 35 years. The rebuilding time for strategy 3, T_{target}, was within the range between the lower and upper limits (Table 1).

The results from the cyclic model and autocorrelated model differ somewhat (Table 1). If the amplitude of the cycle was theoretically high enough, the stock would rebuild with certainty for all replicates within one cycle length with the cyclic recruitment function, whereas achievement of 100% rebuilding probability was problematic with the autocorrelated recruitment function. Also, changes in simulated population abundances (not illustrated) and rebuilding probabilities over time were much more gradual with the autocorrelated curve than with the cyclic curve (Figure 1). For base models, fewer years were required to achieve ≥50% and ≥90% rebuilding probabilities with the cyclic model than with the autocorrelated model, whereas the opposite was true for the number of years to achieve a ≥10% rebuilding probability (Table 1).

Rebuilding times, probabilities of fishery closure, and mean annual yields were generally sensitive to stock–recruitment dynamics (Table 1). Depensation on the stock–recruitment curve generally prolonged the rebuilding time and resulted in a higher probability of fishery closure and a lower mean yield with a planning horizon of 10 years or longer. A lower autocorrelation coefficient reduced rebuilding time and probability of

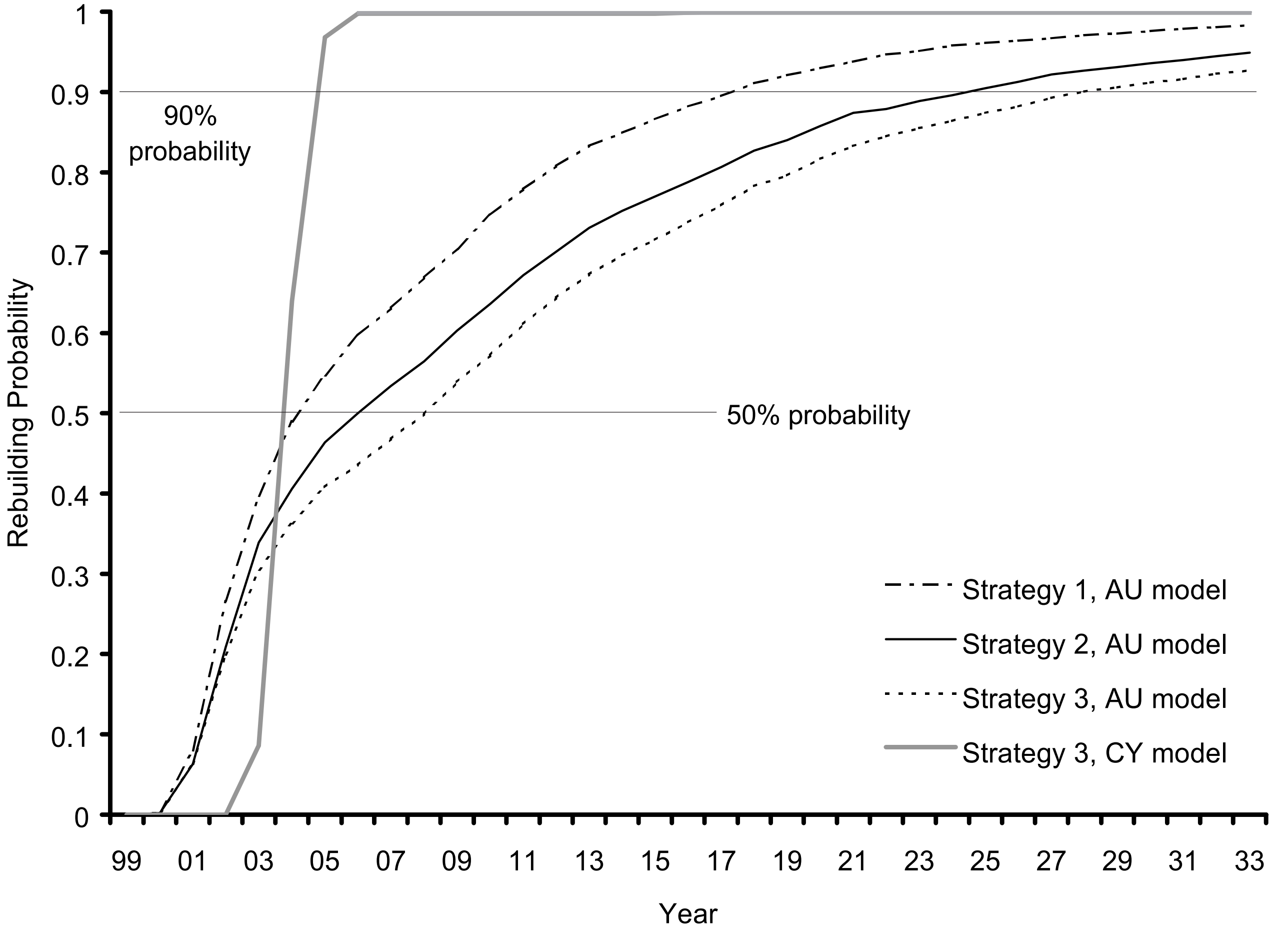

Figure 1. Estimated rebuilding probabilities for 3 rebuilding strategies for eastern Bering Sea Tanner crabs with autocorrelated (AU) and cyclic (CY) stock–recruitment models.

fishery closure and increased mean yield. By contrast, a higher autocorrelation coefficient greatly increased rebuilding time and probability of fishery closure. Mean yield decreased with higher handling mortality rates. As expected, a longer recruitment cycle increased rebuilding time (Figure 3) and probability of fishery closure (Table 1). Rebuilding times were similar between low and high recruitment-cycle amplitudes (Figure 3), but the high amplitude reduced the fishing opportunities considerably because the probability of fishery clo-

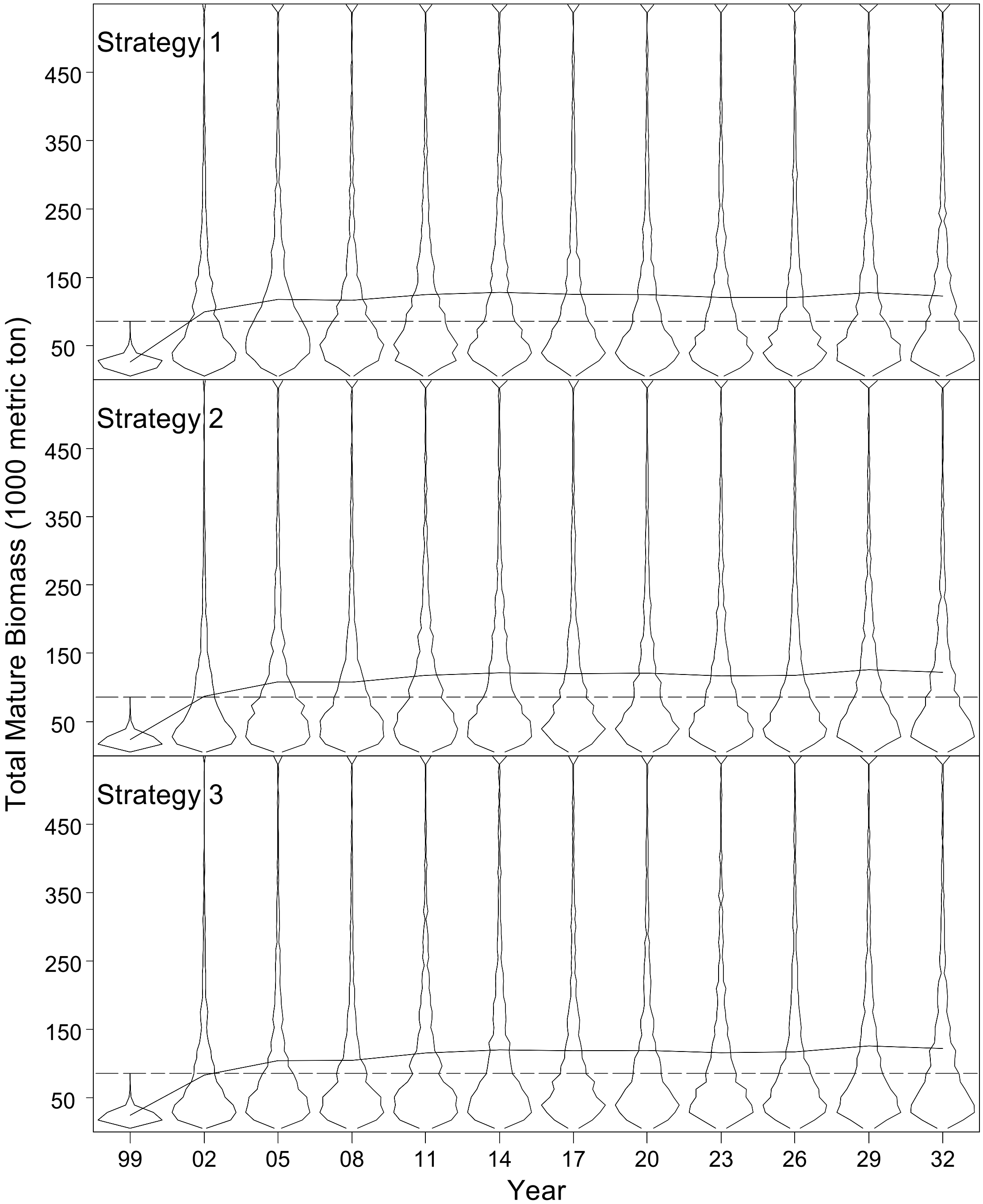

Figure 2. Frequency distributions (bell shapes) of total mature biomass of eastern Bering Sea Tanner crabs with 3 rebuilding strategies under the autocorrelated stock–recruitment model. Solid lines are mean mature biomass, and dashed lines represent the biomass that produces MSY.

Table 1. Comparisons of years required to achieve ≥10%, ≥50%, and ≥90% rebuilding probabilities (RP), probabilities of fishery closure, and mean annual yields within 5, 10, and 20 years for 3 rebuilding strategies under different assumptions of stock–recruitment (S–R) models and handling mortality (HM). AC denotes autocorrelation coefficient.

	Years at RP			Fishery Closure			Mean Annual Yield (mt)		
Scenarios	≥ 10%	≥ 50%	≥ 90%	5 years	10 years	20 years	5 years	10 years	20 years
Strategy 1 During Rebuilding Period									
Autocorrelated S–R model									
Base model	4	7	20	0.85	0.68	0.54	1,886.0	3,701.3	5,023.4
Depensatory	4	7	26	0.85	0.70	0.57	1,886.0	3,192.4	4,537.3
Low AC (0.4)	3	5	9	0.74	0.47	0.31	3,095.6	4,687.8	5,719.2
High AC (0.95)	9	>35	>35	0.99	0.96	0.91	63.6	612.5	2,040.3
HM = 0.0	4	7	20	0.85	0.67	0.53	1,958.8	3,950.8	5,386.0
HM = 0.5	4	7	20	0.85	0.68	0.54	1,775.7	3,329.3	4,470.6
Cyclic S–R model									
Base model	5	6	7	0.96	0.49	0.46	243.7	5,619.5	4,446.2
8-year cycle	4	4	5	0.70	0.46	0.29	3,390.4	4,587.5	4,647.3
21-year cycle	7	9	10	1.00	0.76	0.48	0.0	2,235.3	5,538.3
0.75 amplitude	5	5	6	0.89	0.45	0.30	665.4	5,179.7	4,641.5
1.75 amplitude	6	6	7	0.99	0.51	0.55	55.4	5,853.5	4,361.2
Strategy 2 During Rebuilding Period									
Autocorrelated S–R model									
Base model	4	8	27	0.88	0.72	0.59	1,542.3	3,273.9	4,598.1
Depensatory	4	10	>35	0.88	0.75	0.63	1,542.3	2,787.7	4,010.4
Low AC (0.4)	3	5	12	0.78	0.54	0.35	2,524.3	4,125.0	5,422.8
High AC (0.95)	11	>35	>35	1.00	0.97	0.93	45.8	524.5	1,812.3
HM = 0.0	4	8	27	0.88	0.72	0.58	1,604.3	3,500.3	4,934.5
HM = 0.5	4	8	27	0.88	0.73	0.60	1,448.8	2,937.7	4,086.6
Cyclic S–R model									
Base model	6	6	7	0.98	0.52	0.47	94.7	5,084.0	4,175.2
8-year cycle	4	5	5	0.74	0.50	0.30	2,828.4	4,085.7	4,566.1
21-year cycle	8	9	11	1.00	0.84	0.51	0.0	1,482.1	4,914.4
0.75 amplitude	5	6	7	0.95	0.50	0.32	320.0	4,648.7	4,393.2
1.75 amplitude	6	6	7	1.00	0.54	0.56	18.5	5,316.1	4,079.2
Strategy 3 During Rebuilding Period									
Autocorrelated S–R model									
Base model	4	10	30	0.64	0.52	0.44	2,173.9	3,768.8	4,937.8
Depensatory	4	12	>35	0.64	0.56	0.50	2,173.9	3,246.0	4,311.6
Low AC (0.4)	3	5	14	0.46	0.30	0.22	3,386.1	4,655.0	5,709.4
High AC (0.95)	13	>35	>35	0.97	0.92	0.88	135.4	650.0	1,928.9
HM = 0.0	4	10	29	0.64	0.51	0.43	2,317.1	4,086.4	5,340.7
HM = 0.5	4	11	33	0.64	0.53	0.45	1,964.0	3,305.0	4,331.2
Cyclic S–R model									
Base model	6	6	7	0.66	0.33	0.38	896.2	5,358.3	4,311.1
8-year cycle	4	5	5	0.51	0.38	0.24	3,251.0	4,221.2	4,647.9
21-year cycle	9	10	11	0.89	0.48	0.33	220.2	2,365.4	5,258.6
0.75 amplitude	5	6	7	0.52	0.26	0.20	1,381.6	5,027.7	4,581.1
1.75 amplitude	6	6	7	0.77	0.39	0.49	565.5	5,527.9	4,183.3

sure increased. Generally, under the same conditions, strategy 1 had the shortest rebuilding times, strategy 2 had the highest probabilities of fishery closure and the lowest mean yield, and strategy 3 had the longest rebuilding times and the lowest probabilities of fishery closure. However, for many scenarios, all 3 rebuilding strategies resulted in similar rebuilding times.

DISCUSSION

The responses of the 3 rebuilding strategies were generally expected. Total mortality was lowest for strategy 1 and highest for strategy 3, resulting in the shortest rebuilding time for strategy 1 and longest for strategy 3. Without directed fishing mortality for both strategies 1 and 2 the longer rebuilding time caused a higher probability of fishery closure for strategy 2, whereas the lowest fishery threshold provided the highest fishing opportunity for strategy 3. Because of the low harvest rate when the biomass was below B_{msy} and the low bycatch rate of females due to their relatively small body size, fishing mortality was generally low with strategy 3 when the stock abundance was low. This feature, together with a weak density-dependent stock–recruitment relationship, explains why all 3 rebuilding

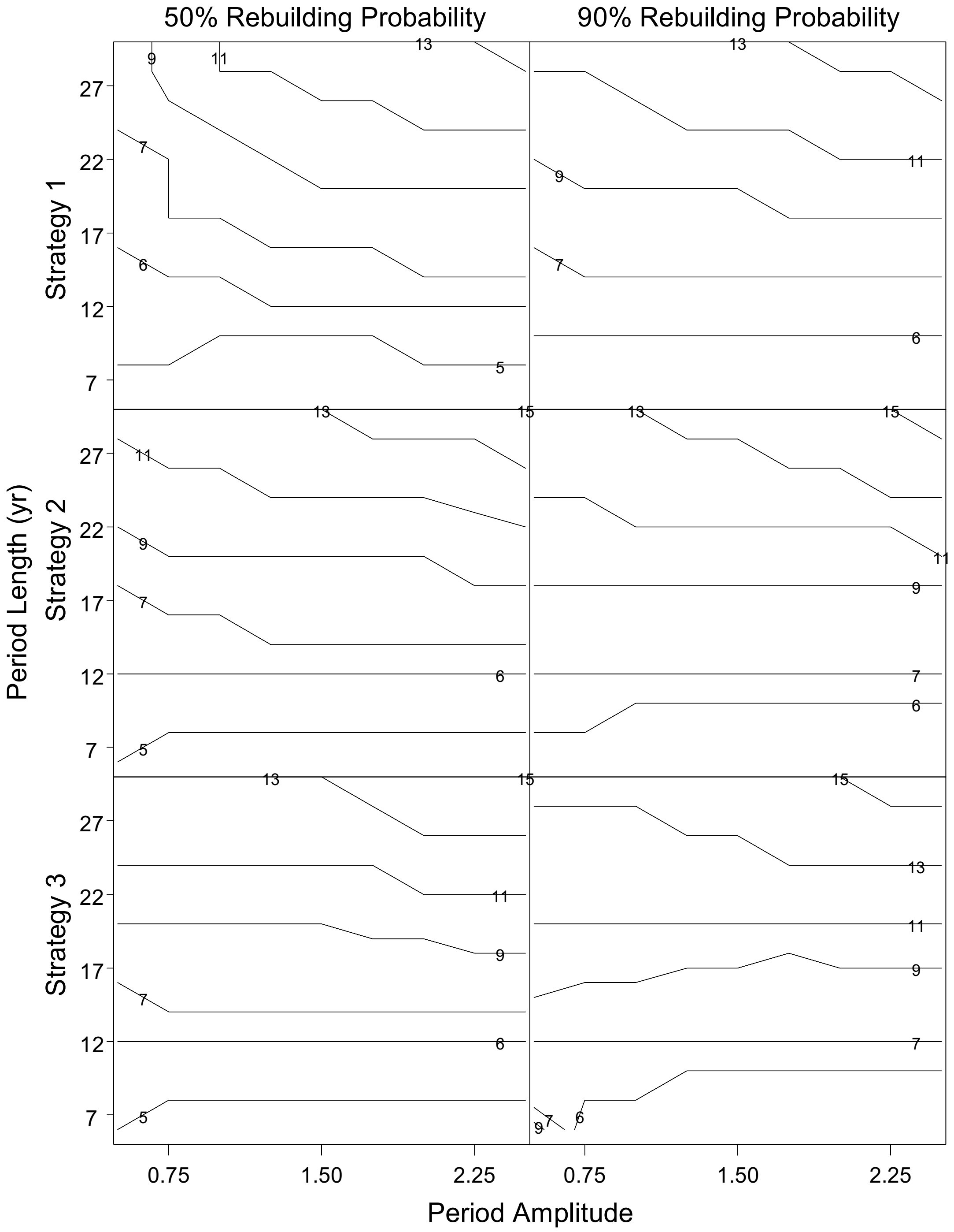

Figure 3. Contour plots of years required to achieve ≥50% and ≥90% rebuilding probabilities by period amplitude and period length of the cyclic stock–recruitment model for eastern Bering Sea Tanner crabs. The plots are classified by 3 rebuilding strategies and 2 rebuilding probabilities.

strategies resulted in similar rebuilding times for many scenarios. With the lowest probability of fishery closure, strategy 3 provides the greatest fishing opportunity as well as the highest short-term yield.

Both autocorrelated and cyclic Ricker curves fit the stock–recruitment data equally well, and we cannot evaluate the merits of the 2 alternatives for eastern Bering Sea Tanner crabs with confidence using the existing data. In an earlier study we used the cyclic curve to evaluate harvest strategies (Zheng and Kruse 1999b). In this study we found that the rebuilding probability of this depressed stock is largely determined by recruitment-cycle length, which is subject to uncertainty. If the cyclic curve is used to estimate rebuilding

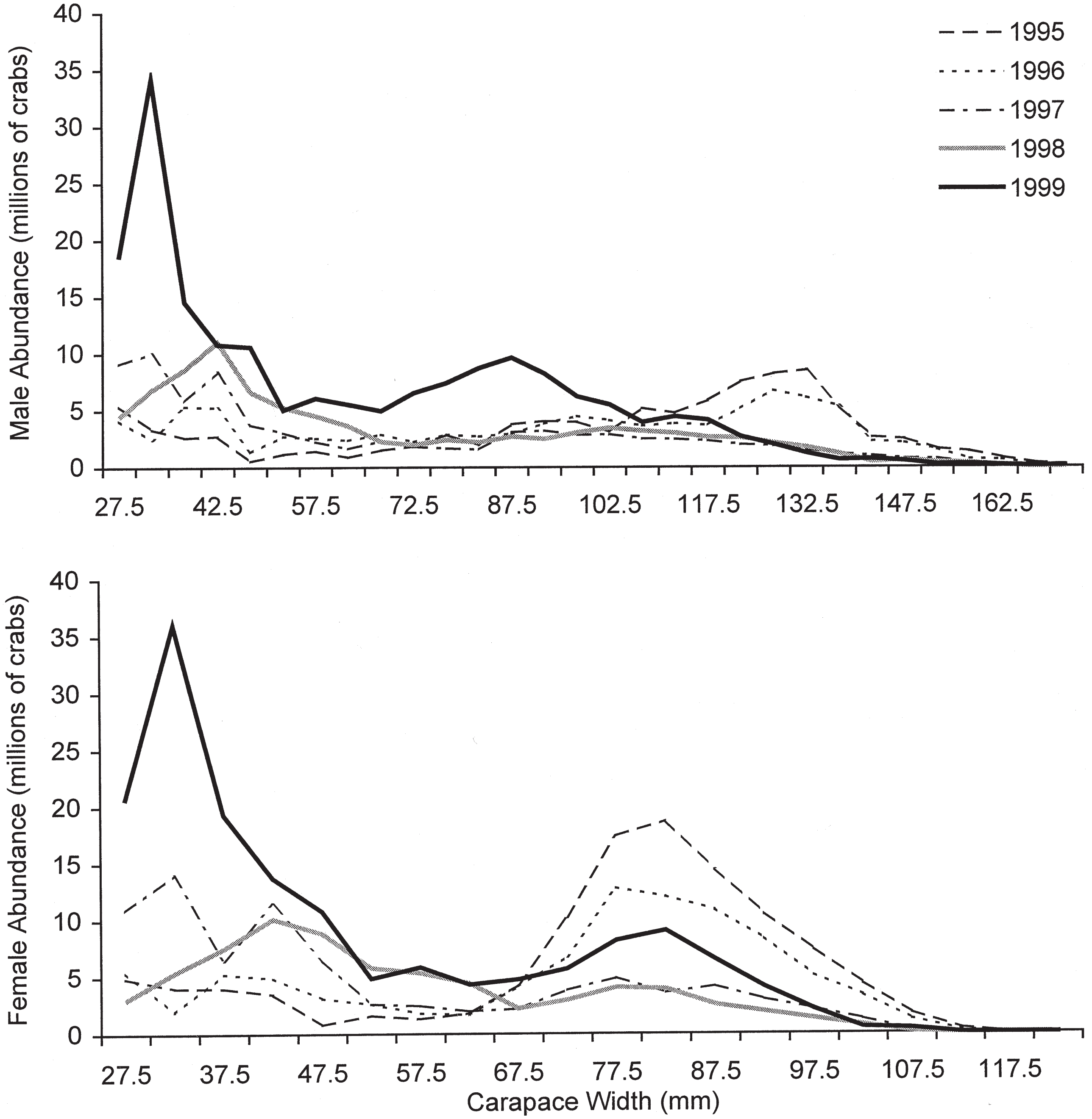

Figure 4. Size-frequency distributions of male (top panel) and female (bottom panel) Tanner crabs in the Eastern District of the eastern Bering Sea from NMFS trawl surveys during 1995–1999. Abundance estimates are based on area-swept methods.

probability, we must make assumptions about the length and amplitude of the current recruitment cycle. Cycle length and amplitude are randomly generated with the autocorrelated curve, thus avoiding these assumptions. The timing of the next strong series of year classes will bear heavily on our interpretation of cyclic and autocorrelated recruitment.

Although periodic bursts of recruitment for eastern Bering Sea Tanner crabs have been regular over the short history of observations, future patterns of recruitment are uncertain. Some stocks of Tanner and red king crabs *Paralithodes camtschaticus* in the Gulf of Alaska have been depressed for nearly 2 decades, following 20–30 years of periodic recruitment (Zheng and Kruse 2000). For some of these stocks, either previous patterns of periodic recruitment have disappeared, or the cycle lengths have greatly increased. For eastern Bering Sea Tanner crabs, we cannot rule out the possibility that density-dependent stock effects are more important at very low stock sizes than environmental factors. Depensation in the stock–recruitment curve may occur at extremely low stock sizes owing to several mechanisms: (1) highly aggregating species such as Tanner crabs (Stevens et al. 1994) may suffer higher rates of predation at low stock sizes (Clark 1974), (2) potential mates may have difficulty finding one another at low densities, and (3) critical densities of larval or juvenile crabs may be required to compensate for predation mortality that otherwise constrains year class success.

Survey data in recent years suggest the apparent 13–14 year recruitment cycle may repeat. During the last upswing in recruitment, a high abundance of crabs of 60–90 mm CW was first detected by the survey in 1987. If the cycle holds, high abundance of similar-sized crabs will be expected in 2000 or 2001. During the National Marine Fisheries Service stock assessment surveys of the Eastern District of the eastern Bering Sea during 1995–1999, modes of juvenile Tanner crabs occurred at approximately 37.5 mm CW in 1996, 32.5 mm and 42.5 mm in 1997, 42.5 mm in 1998, and 32.5 mm in 1999 (Figure 4). The CW modes of 82.5 mm and 87.5 mm (males) in 1999 were caused primarily by crabs from a single survey station. The lack of consistent modal progression over these 4 years is inconsistent with expected growth rates associated with a strong year class. Survey catches of juvenile Tanner crabs <70 mm CW are often unreliable indices of year class strength. Because survey catchability fluctuates with crab size from year to year, size frequency data on juveniles must be interpreted cautiously. Notwithstanding this caveat, relative abundance of new-shell crabs 25–100 mm CW has been increasing since 1995. Consistent modal progression also was not observed before the occurrence of strong recruitment in 1987 and 1988. The high survey abundance of small new-shell crabs in 1999 gives us some hope the observed recruitment cycle may be repeated. It is too early to tell whether the apparent high juvenile abundance in 1999 is an indicator that strong year classes are imminent. If it is an indicator, the rebuilding time will be shorter than those estimated in our analysis. If high juvenile abundance estimates in 1999 were caused by survey measurement errors, the current recruitment cycle will be longer than previously observed, and the realized rebuilding time will be longer than we estimated here.

Recent research on environmental factors affecting year class strength of eastern Bering Sea Tanner crabs statistically supported the following hypotheses: (1) cold bottom-water temperature adversely affects the reproductive population by interrupting or delaying egg development and disrupting the timing of mating and/or hatching, and (2) northeast winds along the north side of the Alaska Peninsula may promote coastal upwelling while advecting larvae to preferred offshore habitats of fine mud and sand for settlement (Rosenkranz et al. 1998, *in press*).

Statistical modeling with bottom temperature, surface temperature, and wind data suggests recruitment to the surveyed stock should increase from 1997 through 2000, corresponding to brood years in the late 1980s and early 1990s (Rosenkranz 1998). So far, the survey data do not indicate strong recruitment in 1997 and 1998. If the recruitment starting in 2000 is moderate to strong, consistent with an optimistic interpretation of the survey data on juvenile Tanner crabs, B_{msy} could be attained by the early to middle part of the 2000s. Our optimistic model scenarios predicted similar rebuilding periods.

There are many caveats to such forecasts. During 1965 to 1985 bottom temperature and northeast winds were positively related and appeared to contribute synergistically to recruitment from those brood years. However, during 1986 to 1995 bottom temperature was negatively related to northeast winds, and we cannot sort out their competing positive and negative roles on Tanner crab year class strength at this time. Declining bottom temperatures during this period are expected to negatively affect reproduction, but increasing strength of northeast winds is expected to positively influence larval advection to nursery areas. As with analysis of stock–recruitment relationships, longer time series of environmental and recruitment data are necessary to predict cycles in Tanner crab year class strength with any degree of confidence.

In summary, the prospects for Tanner crab stock rebuilding depend largely on future recruitment levels that are difficult to predict despite considerable recent progress on potential recruitment mechanisms. The empirical survey data and computer simulation studies suggest a 50% probability of rebuilding to B_{msy} within 10 years with strategy 3. This rebuilding projection is only 2 years more than the maximum rebuilding rate possible with no directed crab fishing (8 years) and falls within the rebuilding period allowed under the federal guidelines (T_{max} = 10 years). To achieve a 90% rebuilding probability, the rebuilding time is expected to increase to 30 years with strategy 3, 3 years more than the maximum rebuilding rate possible with no directed crab fishing (27 years). Assessment surveys in 2000 and 2001 should reveal whether rebuilding is imminent, or whether a protracted period of stock depression is likely.

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