Center for Independent Experts (CIE) Independent Peer Review Report

on

Review of Eastern Bering Sea Tanner Crab Assessment

June 9 - 11, 2026

Prepared by

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August 2026

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I. Executive Summary

Review of Eastern Bering Sea Tanner Crab Assessment Review was held in person in Seattle, Washington from June 9 - 11, 2026. The CIE review aimed to provide an independent external peer review to evaluate if a pre-defined set of Terms of Reference is addressed to ensure that the stock assessment provides best available information to inform management decisions.

The NOAA Alaska Fisheries Science Center provided the necessary logistics support, documentation, presentation slides, and background information for the review. The Assessment Team (AT) was open in the review process to suggestions and provided additional analyses and information upon request. The review process was transparent and constructive. As a CIE reviewer, I evaluated Eastern Bering Sea Tanner Crab Assessment with respect to the pre-defined Terms of Reference provided by the CIE.

The eastern Bering Sea (EBS) Tanner crab assessment remains one of the most scientifically sophisticated crustacean stock assessments currently in operation. The assessment benefits from an extensive fishery-independent survey program, a long-time series of biological observations, an integrated size-structured assessment model (TCSAM02), rigorous annual review processes, and a precautionary management framework. Overall, I conclude that the assessment is scientifically sound. At the same time, I identified several emerging scientific issues that collectively suggest the assessment is approaching an important transition point. Historically, the primary uncertainties affecting Tanner crab assessments involved recruitment variability, natural mortality, growth, and maturity estimation. While these uncertainties remain important, I conclude that future assessment performance will increasingly depend on addressing broader structural issues, including survey catchability, spatial population structure, climate-driven changes in productivity, hybridization, and the appropriateness of existing biological reference points.

A recurring theme across all Terms of Reference is that the assessment has been developed largely within a stationary, coastwide, single-stock framework. Increasing evidence suggests that this framework may become progressively less representative of the biological and ecological realities of Tanner crab populations in the eastern Bering Sea. Although no immediate changes are warranted, future assessment development should increasingly focus on spatial, environmental, and ecosystem processes that influence stock productivity and management performance.

I conclude that GMACS (General Model for Assessing Crustacean Stocks) represents a promising long-term assessment platform and offers several advantages, including improved transparency, standardization across crab stocks, maintainability, and flexibility for future model development. No scientific issues were identified that would preclude eventual adoption. However, I do not believe that GMACS is yet ready to replace TCSAM02 as the operational assessment model. Demonstration of equivalence remains incomplete, particularly regarding optimized model behavior, retrospective performance, and management outputs such as OFLs and stock-status determinations. I support continued parallel operation of TCSAM02 and GMACS while objective transition criteria are established and evaluated.

The side-by-side (SBS) study represents one of the most important methodological advances reviewed during this assessment cycle. The analyses provide compelling evidence that NMFS survey catchability is strongly size-dependent, and that smaller Tanner crab are sampled less efficiently than previously assumed. I found the SBS methodology scientifically rigorous and biologically plausible. However, uncertainty regarding absolute catchability remains substantial. As a result, the review does not support immediate replacement of existing survey selectivity assumptions within the operational assessment. The most important conclusion is that survey observation uncertainty may be as influential as biological uncertainty in determining assessment outcomes. Future assessments should therefore explicitly account for uncertainty associated with survey selectivity and catchability.

I conclude that the biological justification for the current F35%/B35% framework is weaker than generally recognized. Several characteristics of Tanner crab complicate interpretation of SPR-based reference points, including terminal molt, disconnect between maturity and fishery selectivity, absence of a demonstrated stock-recruitment relationship, male-only fishery, and increasing environmental nonstationarity. I believe that F35% functions primarily as a management convention rather than a strongly biologically validated representation of stock productivity. Morphometrically mature male biomass remains the most appropriate metric currently available for management use. However, future evaluation of alternative biomass-based and empirical harvest control rules is strongly recommended.

I found substantial evidence for biologically meaningful spatial structure within the Tanner crab population. Evidence includes divergent eastern and western recruitment, differing biomass trajectories, regional maturity differences, environmental associations, and changing spatial distributions. However, available evidence does not support immediate implementation of a two-area assessment model. The most scientifically defensible interpretation is that Tanner crab function as a spatially structured metapopulation rather than either a homogeneous stock or two fully independent populations. The key question is not whether there are two stocks, but whether spatial structure materially affects management performance. This question should be addressed through spatial operating models and Management Strategy Evaluation (MSE).

I believe hybridization represents the most novel biological issue identified during the review. I agree that hybrids should remain outside the operational assessment framework at present because critical biological information remains unavailable, including fertility, reproductive contribution, growth, mortality, and recruitment dynamics. However, I strongly disagree with any interpretation that hybridization is biologically unimportant. Increasing hybrid abundance may indicate broader ecosystem changes, altered species interactions, and climate-driven redistribution of Tanner and snow crab populations. Consequently, hybridization should be viewed as a strategic uncertainty requiring substantial future research.

Overall, I conclude that the eastern Bering Sea Tanner crab assessment is supported by one of the most comprehensive and scientifically rigorous crustacean monitoring and assessment programs currently available. The assessment benefits from a long-term NMFS fishery-independent survey, extensive fishery-dependent monitoring, detailed biological sampling, and a sophisticated integrated assessment model (TCSAM02) that explicitly incorporates key biological processes including growth, maturity, shell condition, recruitment, fishing mortality, and selectivity. Confidence in assessment outputs is further strengthened by multiple layers of scientific review through the assessment team, Crab Plan Team, Scientific and Statistical Committee (SSC), and independent CIE review process. In addition, the assessment team should be commended for proactively addressing emerging scientific issues, including revised maturity estimation methods, survey selectivity studies, spatial population structure, hybridization, and development of the GMACS framework, demonstrating a strong commitment to continuous improvement and scientific advancement.

Despite these considerable strengths, this review identified several important weaknesses and emerging challenges that are likely to influence future assessment performance and management effectiveness. The most significant issue is the growing mismatch between the spatial scale of the federal stock assessment and the spatial scale of fishery management. NOAA Fisheries currently assesses Tanner crab as a single coastwide stock and derives coastwide reference points, OFLs, and ABCs, whereas the State of Alaska manages the fishery through separate eastern and western management areas with area-specific TACs and management actions. As evidence accumulates for regional differences in recruitment, maturity schedules, biomass trends, and environmental drivers, this disconnect between assessment and management may become increasingly problematic. A recurring theme throughout this review is that the assessment and management systems are evolving at different rates. While state management has already adopted a spatially explicit approach through separate eastern and western harvest strategies, the assessment framework remains largely coastwide and assumes relatively homogeneous productivity. Consequently, assessment outputs and management decisions are not always fully aligned. This issue is likely to become more important as spatial productivity differences increase, climate change alters species distributions, and the risk of localized depletion grows. I, therefore, recommend stronger integration between assessment and management through routine east-west reporting of biological indicators, regional biomass estimates, area-specific projection analyses, development of spatial operating models, and MSE of alternative regional harvest strategies. Such efforts would improve consistency between federal scientific advice and state management implementation while providing a stronger foundation for future Tanner crab conservation and fishery sustainability. I made the following prioritized research recommendations:

High (short-term) Priority

- Develop a Spatial Operating Model and Conduct MSE - this is the single most important recommendation emerging from the review. An MSE framework would allow evaluation of current management, spatial harvest strategies, empirical harvest control rules, and climate-informed management.
- Quantify Survey Catchability Uncertainty - survey catchability uncertainty should be incorporated into assessment uncertainty, OFL calculations, and projections.
- Evaluate Alternative Harvest Control Rules - particular attention should focus on empirical biomass-based rules, mature male biomass thresholds, and regional harvest strategies.

Medium (medium-term) Priority

- Improve Understanding of Connectivity - research should focus on tagging studies, larval transport, movement rates, and source-sink dynamics.
- Expand Hybrid Research - priority topics include fertility, reproductive contribution, growth, mortality, and climate drivers.
- Continue GMACS Development - parallel model operation should continue until equivalence is demonstrated.

Low (long-term) Priority

- Develop Environmental Diagnostics - future assessments should routinely evaluate cold-pool dynamics, bottom temperature, environmental productivity indicators.
- Evaluate Localized Depletion Risk - assessment simulations should determine whether coastwide management adequately protects regional populations.

II. Background

Tanner crab (*Chionoecetes bairdi*) is one of the principal commercially harvested crab species in Alaska and an important component of the eastern Bering Sea (EBS) benthic ecosystem (Kruse et al. 2025). Tanner crab are distributed throughout the eastern Bering Sea shelf and occur across a broad range of depths and habitats. Their distribution is influenced by bottom temperature, sediment type, ontogenetic stage, and oceanographic conditions (Richar 2014; Weems 2024).

Tanner crab exhibit several biological characteristics that make assessment and management challenging. Most importantly, they undergo a terminal molt to maturity. Prior to terminal molt, individuals continue to grow through successive molts (Tamone et al. 2007). Following terminal molt, growth ceases permanently. Consequently, maturity, growth, and fishery recruitment are tightly coupled biological processes. Errors in estimating maturity schedules can directly influence estimates of future legal and exploitable biomass, reproductive biomass, and stock productivity. Tanner crab exhibit sexual dimorphism, with males attaining substantially larger sizes than females (Stevens et al. 1993). Fisheries primarily target mature males exceeding legal size limits. Reproductive success depends on the availability of mature males and females and may be influenced by population density, size structure, and environmental conditions. Recruitment is highly variable and appears to be influenced by a combination of environmental conditions, larval transport processes, habitat suitability, and survival during early life stages (Nielsen et al. 2007; Richar 2014). Like many crab populations, Tanner crab exhibit episodic recruitment pulses, resulting in periods of rapid population increase followed by periods of relatively low recruitment.

The eastern Bering Sea Tanner crab fishery is one of Alaska's historically important commercial crab fisheries and has contributed substantially to the economic viability of fishing communities, processors, and regional economies throughout western Alaska. The fishery targets legal-sized mature males and is managed under the Bering Sea/Aleutian Islands (BSAI) Crab Fishery Management Plan jointly administered by the National Marine Fisheries Service (NMFS) and the State of Alaska. Management includes annual stock assessments; annual overfishing limit (OFL) and acceptable biological catch (ABC) recommendations; total allowable catch (TAC) specifications; size limits; sex restrictions; seasonal closures; and observer monitoring programs.

Although the federal assessment treats eastern Bering Sea Tanner crab as a single stock, the State of Alaska manages harvest through separate eastern and western management areas divided approximately at 166°W longitude. Recent years have been characterized by substantial differences in abundance and recruitment between eastern and western regions (Stockhausen 2026), creating increasing interest in whether current management and assessment frameworks adequately capture regional population dynamics.

The Tanner crab stock is currently assessed using the Tanner Crab Assessment Model (TCSAM02), a size-structured population dynamics model specifically developed to represent the unique biology and fishery dynamics of Tanner crab (Stockhausen 2018). The model was designed to account for the complex life-history characteristics of crab populations, including terminal molt, size-dependent maturity, shell-condition transitions, and multiple fishery and survey observation processes. TCSAM02 tracks the Tanner crab population through time by partitioning individuals into biologically meaningful categories based on sex (male and female); size class (carapace width categories); maturity state (immature and mature); and shell condition (new-shell and old-shell categories). This structure allows the model to explicitly represent growth, maturation, recruitment, mortality, and fishery selectivity processes that differ among demographic groups. The model simulates the annual dynamics of the Tanner crab population through a sequence of biological processes, including (1) recruitment defined as new individuals entering the population through annual recruitment processes and estimated from the data and represents the addition of young crab to the modeled population; (2) growth and molting with immature individuals growing through successive molts, moving among size classes according to estimated growth-transition probabilities (because Tanner crab undergo a terminal molt, growth and maturity are closely linked within the model); (3) maturation with the model estimating size-dependent probabilities of terminal molt and maturity, which is particularly important because mature males cease growing after terminal molt and become available to the fishery; (4) natural mortality applied annually and representing losses due to predation, disease, environmental factors, and other non-fishing causes; (5) fishing mortality quantifying fishery removals estimated using observed catch data and fishery selectivity patterns varying among size classes and demographic groups depending on fishery regulations and fishery behavior; (6) observation models integrating multiple fishery-dependent and fishery-independent data sources through a series of observation models; (7) fishery-independent survey data with the information from the NMFS eastern Bering Sea bottom trawl survey, including abundance indices; biomass estimates; size compositions; maturity observations; and shell-condition observations, providing the primary information on population abundance, size structure, and spatial distribution; (8) fishery-dependent data including retained catch; total removals; fishery size compositions; and fishery effort information, informing estimates of fishing mortality and fishery selectivity; (9) biological sampling data including maturity observations; growth-transition data; and shell-condition information, improving estimation of key life-history processes; (10) parameters estimated by the model with integrated data sources described above to estimate several key biological and fishery processes including annual recruitment; growth-transition probabilities; maturity schedules; natural mortality; fishing mortality; survey selectivity; fishery selectivity; population abundance and biomass.

The primary outputs generated by TCSAM02 include mature male biomass (MMB); legal male biomass; stock abundance trajectories; recruitment estimates; fishing mortality estimates; stock-status indicators; OFLs; ABCs; short-term population projections. These outputs provide the scientific basis for annual management advice and harvest specifications.

The Tanner crab assessment operates within the BSAI Crab Fishery Management Plan Tier System. Because a reliable stock-recruitment relationship has not been established, Tanner crab are currently managed under a Tier 3 framework, which uses spawning-potential-ratio (SPR)-based proxy reference points. The principal biological reference points include F35%, the fishing mortality rate that reduces spawning potential to 35% of its unfished level; and B35%, the corresponding biomass proxy used in stock-status determinations. These reference points are used to determine stock status, establish harvest control rules, calculate overfishing limits, and support annual management decisions.

The eastern Bering Sea Tanner crab management system is among the most scientifically advanced crustacean management systems currently operating worldwide. It combines comprehensive fishery-independent monitoring, sophisticated stock assessment methods, precautionary harvest control rules, and extensive peer review within a cooperative federal-state governance framework.

The system has been successful in preventing chronic overfishing and providing science-based management advice. However, several emerging challenges may require future adaptation, particularly regarding spatial stock structure, survey catchability, environmental change, and hybridization. The current management framework remains scientifically defensible and effective, but continued evolution will likely be necessary to ensure that management remains responsive to changing biological and ecosystem conditions.

Recent assessment cycles have identified several important scientific questions regarding survey catchability, maturity estimation, spatial stock structure, and emerging hybridization between Tanner crab and snow crab. Concurrently, efforts have been underway to transition the assessment from TCSAM02 to GMACS (General Model for Assessing Crustacean Stocks), a generalized assessment framework intended to support multiple Alaska crab stocks.

The overarching goal of the Tanner crab assessment is to provide scientifically defensible estimates of stock status and future productivity to support sustainable management of the eastern Bering Sea Tanner crab fishery. Specific objectives of the current assessment cycle include:

- Evaluating readiness of GMACS as a future operational assessment framework.
- Evaluating new survey selectivity information from side-by-side trawl studies.
- Assessing effects of revised maturity estimation methods.
- Evaluating biological reference points and stock-status calculations.
- Examining evidence for spatial stock structure and implications for assessment design.
- Evaluating the potential effects of increasing hybrid abundance.
- Providing updated estimates of stock status, OFLs, ABCs, and future stock trajectories.

Collectively, these efforts are intended to improve understanding of Tanner crab population dynamics, reduce uncertainty in assessment results, and ensure that management advice remains scientifically sound under changing biological and environmental conditions.

The purpose of this review was to evaluate the scientific basis of these developments and provide recommendations regarding their incorporation into future assessment and management processes. The review encompassed a comprehensive evaluation of the eastern Bering Sea Tanner crab assessment and supporting analyses, including the annual Stock Assessment and Fishery Evaluation (SAFE) report, GMACS transition and model comparison studies, side-by-side survey catchability and selectivity investigations, male maturity estimation analyses, spatial stock structure evaluations, hybrid Tanner–snow crab studies, the 2025 eastern Bering Sea crab survey report, and associated appendices and model documentation. Particular emphasis was placed on assessing the scientific validity of the assessment framework, identifying major sources of uncertainty, evaluating the implications of these uncertainties for stock status determination and management advice, and determining the readiness of proposed methodological developments for incorporation into the operational assessment and management process.

As a CIE reviewer, I was tasked to evaluate the Review of Eastern Bering Sea Tanner Crab Assessment with respect to the Terms of Reference provided by the CIE. This report is prepared following the required format including an executive summary (Section I), a background introduction (Section II), a description of my role in the review activities (Section III), my comments on each item listed in the Terms of Reference (ToRs, Section IV), a summary of my comments and recommendations (Section V), and references (Section VI). The final part of this report (Section VII) includes a collection of appendices including the Statement of Work (SoW).

III. Description of the Individual Reviewer's Role in the Review Activities

My role as a CIE independent reviewer was to conduct an impartial and independent peer review of the Review of Eastern Bering Sea Tanner Crab Assessment with respect to the pre-defined Terms of Reference. About two weeks prior to the review workshop at the NOAA Alaska Fisheries Science Center, the Assessment Report and supporting working papers were provided to the reviewers. I downloaded all the materials on the Review of Eastern Bering Sea Tanner Crab Assessment, and read all the relevant documents downloaded (see the list in Appendix I). I also collected and read references relevant to the topics covered in the reports and the SoW prior to my trip to the review.

The in-person CIE review workshop was held from June 9-11, 2026, at the NOAA Alaska Fisheries Science Center (see Appendix II for the schedule). The three days of reviews were chaired by Dr. Cody Szuwalski of Alaska Fisheries Science Center and attended by both federal and state scientists and other stakeholders from various organizations (see the List of Participants in Appendix III).

Presentations were given during the four days of review to provide the CIE reviewers with the relevant information. Additional analyses were requested during the review, and the AT accommodated all the requests by the Review Panel. I was actively involved in the discussions during the presentation by questioning and making comments and suggestions. I also discussed relevant issues with fellow reviewers.

IV. Summary of Findings

My detailed comments on each item of the TORs are provided under their respective subtitles from the TORs (see below).

ToR 1: Generalized Model for Assessing Crustaceans Stocks (GMACS)

The transition from the bespoke TCSAM02 assessment model to GMACS represents one of the most consequential decisions facing the Tanner crab assessment program. In principle, the transition offers substantial benefits. GMACS provides a generalized assessment platform capable of supporting multiple Alaska crab assessments within a common framework. Such standardization would improve reproducibility, transparency, maintainability, and long-term sustainability of assessment development.

The assessment team has made substantial progress toward demonstrating equivalence between TCSAM02 and GMACS. The GMACS implementation successfully reproduces many of the key population quantities generated by TCSAM02, and recent work has resolved several important issues associated with fishery size compositions and sex-specific fishing mortality calculations. These achievements represent a significant technical accomplishment and demonstrate that the biological processes represented in TCSAM02 can largely be replicated within GMACS. However, the evidence presented during the review does not yet support full operational adoption of GMACS. Although initialization equivalence has largely been achieved, optimized equivalence has not yet been demonstrated. Remaining discrepancies in OFL calculations, parameter estimation, likelihood implementation, and model convergence indicate that GMACS remains under development. Equivalence at a fixed parameter set is not equivalent to demonstrating that two models will converge to the same solution when fit to data.

I think that the primary scientific concern is not whether GMACS is capable of reproducing TCSAM02. Rather, the concern is whether the differences that remain unresolved could influence management quantities such as mature male biomass, OFL, ABC, and stock status determinations. Until these questions are resolved, operational implementation would be premature.

I conclude that GMACS represents a promising long-term framework for Tanner crab assessment and should continue to be developed. However, current evidence supports continued use of TCSAM02 as the operational assessment model. I made the following recommendations for future development and evaluation of GMACS:

1. Continue Parallel Operation of TCSAM02 and GMACS

I recommend continued parallel operation of TCSAM02 and GMACS during the next assessment cycles. Although substantial progress has been made in reproducing Tanner crab assessment results within GMACS, the current evidence does not yet demonstrate complete operational equivalence between the two frameworks. Running both models concurrently will allow the assessment team to identify remaining differences in parameter estimation, model fits, stock-status determinations, and harvest recommendations while minimizing risk to the management process. Parallel operation will also provide opportunities to evaluate model performance under multiple recruitment regimes and environmental conditions before GMACS becomes the sole operational assessment framework.

2. Establish Objective Transition Criteria

A formal set of transition criteria should be developed before GMACS is considered for operational implementation. The review recommends that transition decisions be based on predefined quantitative benchmarks rather than subjective judgment. Such criteria could include acceptable differences in mature male biomass estimates, recruitment estimates, OFL calculations, ABC recommendations, retrospective patterns, likelihood values, and parameter estimates. Establishing objective performance metrics will improve transparency, provide clear expectations for model development, and ensure that the transition process is scientifically defensible and reproducible.

3. Demonstrate Optimized Equivalence Prior to Adoption

Most of the comparisons presented during the review focused on reproducing TCSAM02 outputs using common parameter values. While this represents an important milestone, it does not demonstrate that the two models converge to equivalent solutions when independently fitted to the available data. Before GMACS is adopted operationally, the assessment team should demonstrate optimized equivalence by fitting both models independently and comparing resulting parameter estimates, likelihood components, population trajectories, stock-status indicators, and management quantities. Particular attention should be given to differences in recruitment, maturity, natural mortality, fishing mortality, and survey selectivity estimates. Demonstrating optimized equivalence is essential because management advice is generated from estimated rather than fixed parameters.

4. Compare Retrospective Patterns Between Frameworks

Retrospective analyses provide important insight into model consistency, stability, and predictive performance. The review recommends conducting a comprehensive comparison of retrospective patterns produced by TCSAM02 and GMACS using identical datasets and assessment years. Such analyses should evaluate retrospective bias in mature male biomass, recruitment, fishing mortality, and stock-status indicators. Differences in retrospective behavior may reveal structural differences between the two frameworks that are not apparent from single-year comparisons. Understanding these differences will help determine whether GMACS reproduces not only assessment results but also the long-term behavior of the current operational model.

5. Compare OFL and Stock-Status Calculations Under Identical Assumptions

Because management decisions ultimately depend on OFLs, ABCs, and stock-status determinations, particular emphasis should be placed on comparing these outputs between TCSAM02 and GMACS. The review recommends conducting side-by-side analyses under identical assumptions regarding maturity schedules, growth, natural mortality, recruitment, and selectivity. Any differences in OFL calculations, stock-status determinations, or projection results should be fully explained and documented. This comparison is especially important because relatively small differences in model implementation can produce meaningful differences in management advice. Demonstrating consistency in management outputs should be considered a prerequisite for operational implementation of GMACS.

Overall, I conclude that GMACS represents a promising and potentially valuable long-term assessment framework for Tanner crab and other Alaska crab stocks. However, the transition from TCSAM02 should proceed cautiously and be guided by rigorous quantitative evaluation. The primary goal should not simply be to reproduce model outputs, but to demonstrate that GMACS provides equivalent scientific advice, similar management performance, and comparable levels of uncertainty characterization before becoming the operational assessment model.

TOR 1A: Comment on the pros and cons of transitioning from the status quo bespoke assessment to the GMACS framework.

I find that transitioning from TCSAM02 to GMACS offers substantial long-term scientific and operational advantages. At the same time, the transition involves important risks that must be carefully managed to avoid unintended changes in stock assessment results and management advice.

Strengths of Transitioning to GMACS

Standardization Across Crab Assessments: One of the strongest arguments for GMACS is that it provides a unified modeling framework that can be applied across multiple Alaska crab stocks. Currently, different stocks are assessed using stock-specific models that vary in structure, coding, and documentation. A generalized framework improves consistency in assessment methodology, facilitates cross-stock comparisons, and reduces dependence on stock-specific code development.

Improved Transparency and Reproducibility: GMACS is structured as a generalized and well-documented assessment platform. This improves transparency by making model assumptions, parameterization, and likelihood structures more accessible to reviewers and future developers.

Standardization also facilitates independent review and reproducibility, both of which are increasingly important in modern fisheries science.

Long-Term Sustainability: TCSAM02 has evolved over many years and contains considerable stock-specific complexity. As assessment personnel change over time, maintaining and updating specialized models becomes increasingly difficult. GMACS provides a more sustainable long-term framework by reducing reliance on a small number of developers and creating a common infrastructure for future assessment development.

Increased Flexibility for Future Assessment Development: GMACS appears better suited for future incorporation of spatial population structure; environmental covariates; alternative selectivity formulations; ecosystem indicators; management strategy evaluation (MSE); and climate-informed assessment approaches. These capabilities are likely to become increasingly important as assessment priorities evolve.

Successful Representation of Tanner Crab Biology: I find that GMACS successfully captures the major biological processes currently represented in TCSAM02, including recruitment; growth; terminal molt dynamics; maturity; shell-condition transitions; fishing mortality; survey selectivity. This suggests that GMACS is fundamentally capable of serving as an operational Tanner crab assessment framework.

Weaknesses and Risks of Transitioning to GMACS

Incomplete Demonstration of Operational Equivalence: The most important weakness is that full equivalence between GMACS and TCSAM02 has not yet been demonstrated. While initialization comparisons are encouraging, management advice is generated from optimized model fits rather than fixed parameter values. Remaining differences in optimization behavior and OFL calculations indicate that additional work is required before GMACS can be considered fully equivalent.

Potential for Unintended Changes in Management Advice: Small differences in model structure, likelihood implementation, or parameter estimation can propagate through the assessment and affect mature male biomass estimates; recruitment estimates; stock-status determinations; OFLs; and ABC recommendations. Such differences may not be immediately apparent but could have significant management implications.

Loss of Historical Continuity: TCSAM02 has been used operationally for many years, and its behavior is well understood by assessment scientists, managers, and stakeholders. Transitioning to a new framework introduces uncertainty regarding how historical assessment trends should be interpreted and may complicate comparisons with previous assessments.

Increased Complexity During Transition: Running two frameworks simultaneously requires additional effort, computational resources, and documentation. Although this is necessary for a successful transition, it temporarily increases assessment complexity.

Overall, I conclude that the strengths of GMACS substantially outweigh its weaknesses in the long term. However, the benefits of transition will only be realized if equivalence with TCSAM02 is rigorously demonstrated before operational implementation.

TOR 1B: Are there any concerns with the GMACS framework that would preclude its adoption?

I identified no fundamental scientific deficiencies in GMACS that would permanently preclude its adoption as the operational assessment model for eastern Bering Sea Tanner crab. The framework appears biologically realistic, statistically sound, and capable of representing the key population processes necessary for Tanner crab assessment. The review, therefore, concludes that GMACS is a scientifically viable candidate for future operational use. However, several concerns currently preclude immediate implementation.

Concern 1: Optimized Equivalence Has Not Yet Been Demonstrated

Most comparisons presented during the review involved matching outputs under common parameter values. While necessary, these analyses do not demonstrate that GMACS and TCSAM02 converge to equivalent solutions when fitted independently to the data. This is a critical distinction because stock assessment results depend on estimated parameters rather than prescribed parameter values.

Concern 2: Remaining OFL Differences

I noted that differences remain in OFL calculations and some management quantities. Even relatively small discrepancies are important because OFLs directly influence management advice and catch limits. Before adoption, all differences in management outputs should be fully understood and documented.

Concern 3: Incomplete Evaluation of Model Behavior

I found limited information regarding comparative performance of retrospective analyses; parameter identifiability; likelihood profiles; convergence diagnostics; and jitter analyses. These diagnostics are important because they evaluate model behavior rather than simply model outputs.

Concern 4: Structural Differences May Remain

Some remaining differences may reflect structural assumptions rather than coding issues. Such differences should be explicitly identified and evaluated before implementation.

Overall, I conclude that no scientific issues were identified that would permanently prevent adoption of GMACS. Nevertheless, unresolved issues regarding model equivalence, OFL calculations, optimization behavior, and diagnostic performance currently preclude operational implementation.

TOR 1C. If so, are there clear paths to addressing these concerns (and what are the paths)?

I believe that GMACS is approaching operational readiness but that several critical tasks remain before implementation can be recommended.

- ***Demonstrate Optimized Equivalence***
  This should be the highest priority. The assessment team should fit both TCSAM02 and GMACS independently to the same datasets and compare mature male biomass trajectories; recruitment estimates; fishing mortality estimates; stock-status determinations; OFLs; and projections. Equivalence should be evaluated using estimated rather than fixed parameter values.
- ***Resolve Remaining OFL Differences***

All remaining differences in OFL calculations should be reconciled and documented. The review considers consistency in management outputs to be a prerequisite for implementation.

- ***Conduct Comprehensive Retrospective Comparisons***
  Retrospective analyses should be conducted for both frameworks using identical datasets and assessment periods. Comparisons should evaluate retrospective bias; retrospective consistency; and stability of stock-status estimates.
- ***Compare Likelihood Components and Parameter Estimates***
  A component-by-component comparison should be conducted for likelihood values; priors; penalties; parameter estimates; selectivity parameters; mortality estimates; and maturity schedules. This comparison will help identify any remaining structural differences.
- ***Conduct Jitter and Convergence Analyses***
  The review recommends evaluating convergence behavior; sensitivity to starting values; local minima; and parameter identifiability. Equivalent models should exhibit similar convergence characteristics.
- ***Establish Formal Transition Criteria***
  I strongly recommend development of objective criteria that define readiness for implementation. Examples include acceptable differences in mature male biomass estimates; acceptable differences in OFLs; comparable retrospective patterns; and equivalent likelihood values. Such criteria would provide transparency and reduce subjectivity in transition decisions.
- ***Continue Parallel Operation***
  The review recommends maintaining parallel operation of TCSAM02 and GMACS until all transition criteria have been met and reviewed by the Crab Plan Team, SSC, and future independent reviewers.

In summary, GMACS has made substantial progress toward becoming the operational assessment framework for Tanner crab. The remaining work is largely focused on demonstrating equivalence, understanding possible residual and diagnostic differences, and ensuring that management advice generated by GMACS is consistent with that produced by TCSAM02. A cautious, transparent, and evidence-based transition process will provide the greatest confidence in future implementation.

TOR 2. Side-by-Side Selectivity Experiments

The eastern Bering Sea Tanner crab assessment relies heavily on abundance and biomass estimates derived from the NMFS bottom trawl survey. Consequently, assumptions regarding survey catchability and selectivity play a critical role in determining estimates of recruitment, population abundance, mature male biomass, stock status, and future stock projections. Historically, survey selectivity assumptions were based largely on expert judgment and limited empirical information. The side-by-side (SBS) selectivity study represents an important effort to directly evaluate these assumptions by comparing catches obtained from the standard NMFS survey trawl and the BSFRF nephrops trawl across multiple years and locations in the eastern Bering Sea.

I conclude that the SBS study provides scientifically rigorous and management-relevant information regarding Tanner crab survey selectivity. The analyses clearly demonstrate that survey selectivity is strongly size-dependent and that smaller Tanner crab are substantially under-sampled by the NMFS survey gear. However, uncertainty regarding absolute catchability remains substantial, and the current results do not yet justify wholesale replacement of existing selectivity assumptions within the operational assessment framework.

ToR 2A. Are the methods presented for estimating the selectivity of the NMFS survey gear based on the side-by-side experiments scientifically sound?

I conclude that the SBS methodology is scientifically sound and represents one of the most comprehensive evaluations of Tanner crab survey selectivity conducted to date. The study is based on direct experimental comparisons between the NMFS survey trawl and the BSFRF nephrops trawl, providing a strong empirical foundation for evaluating survey catchability. This represents a substantial improvement over reliance on expert judgment or assumed selectivity relationships.

The analytical framework is rigorous and appropriate. The study employs paired-haul comparisons, size-specific catch ratios, generalized additive models (GAMs), random-effects formulations, environmental covariates, bootstrap procedures, and uncertainty analyses. These approaches appropriately account for environmental variation, nonlinear relationships, sampling variability, and uncertainty in parameter estimation. The resulting selectivity estimates are therefore supported by a robust statistical framework.

The results are also biologically plausible and consistent with existing knowledge of Tanner crab behavior and survey gear performance. The finding that smaller Tanner crab are less vulnerable to capture by the NMFS trawl is consistent with expectations regarding crab size, behavior, and known limitations of bottom trawl sampling. However, the review identifies one important limitation. The SBS analyses estimate selectivity relative to the BSFRF nephrops trawl and therefore depend on the assumption that the BSFRF gear provides near-complete capture efficiency. Although this assumption appears reasonable and is supported by available evidence, it has not been independently verified. Consequently, the study provides strong information regarding relative selectivity but does not fully resolve uncertainty regarding absolute catchability.

Overall, I conclude that the SBS methodology is scientifically robust and provides the best available empirical information regarding Tanner crab survey selectivity.

ToR 2B. Are the resulting changes in the scale of the population when incorporating the side-by-side data into the assessment defensible and appropriate for providing management advice?

I conclude that the resulting increases in population scale obtained when incorporating SBS-derived selectivity estimates are biologically plausible and scientifically defensible. The analyses consistently indicate that the NMFS survey under-samples smaller Tanner crab relative to the BSFRF trawl, suggesting that juvenile abundance and total population size may be larger than previously estimated.

I find that these changes are supported by the empirical evidence generated by the SBS experiments and are consistent with the expected effects of correcting for size-dependent survey selectivity. Consequently, the resulting increases in estimated abundance should not be viewed as artifacts of model structure but rather as plausible consequences of improved understanding of the survey observation process. Nevertheless, several important uncertainties remain. The most significant concern is uncertainty regarding the absolute efficiency of the BSFRF trawl. Because the true catchability of the reference gear remains unknown, uncertainty persists regarding the magnitude of the resulting changes in population scale. Additional concerns include potential spatial variation, temporal variation, and environmental influences on catchability that may not be fully represented by the current analyses.

For these reasons, I conclude that the SBS-derived population scaling results are scientifically defensible, but should not yet be regarded as definitive estimates of absolute abundance. Rather, they should be viewed as plausible alternative representations of population scale that help characterize an important source of uncertainty within the assessment.

From a management perspective, I believe that the current evidence is sufficient to recognize survey catchability as a major source of uncertainty but not yet sufficient to replace existing operational selectivity assumptions.

ToR 2C. If not, how would the reviewer approach the provision of management advice using assessment output that incorporates the selectivity experiment data?

Because uncertainty regarding absolute catchability remains unresolved, the review does not recommend immediate adoption of SBS-derived selectivity estimates as the sole basis for operational management advice. Instead, a phased and precautionary approach is recommended.

The first step should be to incorporate SBS information into assessment sensitivity analyses. This would allow managers and assessment scientists to evaluate the influence of alternative selectivity assumptions on recruitment estimates, mature male biomass, stock status, OFLs, ABCs, and future projections without disrupting the continuity of the existing management framework.

Second, assessment uncertainty should be expanded to explicitly include uncertainty associated with survey catchability. The SBS study demonstrates that observation uncertainty may be as important as uncertainty associated with recruitment, growth, or natural mortality. Consequently, future OFL calculations, stock projections, and risk analyses should incorporate uncertainty associated with survey selectivity.

Third, SBS-derived selectivity estimates could be incorporated into the assessment as informative priors rather than fixed assumptions. This approach would allow empirical information from the SBS study to influence parameter estimation while appropriately accounting for remaining uncertainty.

Finally, additional research should focus on estimating the absolute efficiency of the BSFRF trawl and evaluating potential spatial, temporal, and environmental variation in survey catchability. Such work is essential before SBS-derived selectivity estimates can be fully integrated into the operational assessment framework.

Accordingly, I recommend that management advice continue to be based primarily on the existing assessment framework while using SBS results to inform sensitivity analyses, uncertainty characterization, and future assessment development.

In summary, I conclude that the SBS study represents a major scientific contribution to the Tanner crab assessment and provides compelling evidence that NMFS survey selectivity is strongly size dependent. The methodology is scientifically rigorous, biologically plausible, and directly relevant to stock assessment and fisheries management. However, substantial uncertainty remains regarding absolute catchability, spatial variability, temporal variability, *and environmental influences on survey efficiency. I therefore support continued use of the SBS results to improve understanding of survey observation processes while recommending a cautious and phased approach to their incorporation into operational assessment and management advice. Future work should focus on quantifying absolute catchability, incorporating survey uncertainty into stock assessment analyses, and evaluating the consequences of alternative selectivity assumptions for stock status determination and harvest recommendations.*

The side-by-side (SBS) selectivity study provides valuable new information regarding Tanner crab survey catchability and represents an important advancement in understanding survey observation processes. However, the review concludes that the results should be incorporated into the assessment framework cautiously and through a phased approach that acknowledges remaining uncertainty regarding absolute catchability. The following recommendations are prioritized according to their expected importance for improving assessment performance and management advice.

High-Priority Recommendations

- ***Incorporate SBS Results into Assessment Sensitivity Analyses***
  The SBS-derived selectivity estimates should be incorporated into future assessment sensitivity analyses to evaluate their influence on key assessment outputs, including recruitment, mature male biomass, stock status, OFLs, and projections. Sensitivity analyses will allow the assessment team to quantify the effects of alternative selectivity assumptions without immediately altering the operational assessment model. This approach provides a scientifically defensible mechanism for evaluating the robustness of current assessment results while maintaining continuity in management advice.
- ***Explicitly Incorporate Survey Catchability Uncertainty into OFL and Projection Analyses***
  The SBS study demonstrates that uncertainty associated with survey catchability may be larger than previously recognized and could represent one of the major sources of uncertainty in abundance estimation. Future assessments should explicitly propagate catchability uncertainty through stock assessment and projection analyses so that its effects on OFLs, stock-status determinations, and future stock trajectories can be evaluated. This would provide a more realistic characterization of assessment uncertainty and improve the scientific basis for risk-informed management decisions.
- ***Continue Evaluation of Absolute Gear Efficiency***
  The highest scientific priority is to improve understanding of the absolute efficiency of the BSFRF nephrops trawl, which serves as the reference gear in the SBS analyses. While the study provides strong evidence regarding relative selectivity, uncertainty regarding the absolute catchability of the reference gear remains the largest unresolved issue. Additional studies aimed at estimating absolute gear efficiency would substantially improve confidence in abundance estimates and facilitate future incorporation of SBS results into the operational assessment.

Medium-Priority Recommendations

- ***Evaluate Environmentally Varying Selectivity***
  The analyses suggest that survey catchability may vary with environmental conditions, including bottom temperature, habitat characteristics, and substrate composition. Future

work should investigate whether selectivity can be better represented as a dynamic process that varies across environmental conditions rather than as a fixed characteristic of survey gear. Such analyses could improve understanding of spatial and temporal variability in survey performance and help reduce observation bias.

- ***Explore Use of SBS-Derived Information as Informative Priors***
  Rather than replacing current selectivity assumptions directly, the review recommends evaluating whether SBS-derived selectivity estimates can be incorporated into the assessment as informative priors. This approach would allow the assessment model to utilize empirical information from the SBS study while appropriately accounting for uncertainty and avoiding abrupt changes to the operational assessment framework.

Lower-Priority Recommendations

- ***Investigate Geostatistical Approaches to Survey Catchability***
  As assessment methodologies continue to evolve, geostatistical and spatial modeling approaches may provide additional opportunities to account for spatial variation in survey catchability. Such approaches could help identify regional differences in gear performance and improve estimation of abundance in areas where catchability varies due to habitat or environmental conditions. Although this work is not immediately necessary for operational assessments, it may provide valuable insights for future spatially explicit assessment and survey modeling efforts.

In summary, for TOR 2, I conclude that the SBS study provides scientifically robust and management-relevant information regarding Tanner crab survey selectivity. However, uncertainty regarding absolute catchability remains substantial and currently limits direct implementation of the results within the operational assessment. Accordingly, SBS results should initially be incorporated through sensitivity analyses, uncertainty evaluations, and informative priors while additional research focuses on estimating absolute gear efficiency and understanding environmental influences on survey catchability. This phased approach will maximize the scientific value of the SBS study while minimizing risks associated with premature changes to the assessment framework.

TOR 3. Reference Points

Biological reference points form the foundation of the eastern Bering Sea Tanner crab management system and directly influence stock status determinations, OFLs, ABC recommendations, and harvest strategies. The current framework relies on F35% and B35% proxy reference points derived from spawning potential ratio (SPR) calculations. These reference points were originally developed because a reliable stock-recruitment relationship has not been established for Tanner crab.

During this review, I evaluated not only the technical implementation of these reference points but also their biological relevance and management utility. Particular attention was given to the implications of terminal molt, the relationship between maturity and fishery selectivity, recent revisions to maturity estimation, increasing evidence of spatial population structure, environmental change, and the emergence of hybrid Tanner-snow crab populations.

Overall, I conclude that the current F35%/B35% framework remains operationally functional and has served management reasonably well. However, its biological basis for Tanner crab is substantially weaker than is often assumed. The combination of terminal molt, the *disconnect between maturity and fishery selectivity, the absence of a demonstrated stock-recruitment relationship, the male-only nature of the fishery, increasing evidence of spatial structure, and environmental nonstationarity all raise questions regarding whether SPR-based reference points represent the most biologically meaningful basis for future management.*

TOR 3A: Are F35%-based reference points appropriate for Tanner crab in light of terminal molt and the discrepancy between maturity and selection in the fishery?

My conclusion is that F35%-based reference points are operationally acceptable but biologically suboptimal for Tanner crab management. The primary strength of the current framework is that it provides a transparent and precautionary mechanism for determining OFLs and evaluating stock status. It is familiar to managers, stakeholders, and assessment scientists, and it provides continuity with the broader BSAI crab management system. However, following aspects of Tanner crab biology fundamentally weaken the biological interpretation of F35%:

Terminal Molt Creates a Disconnect Between Productivity and SPR

The underlying logic of SPR-based reference points is that maintaining a specified fraction of unfished reproductive capacity will sustain stock productivity. This concept was originally developed largely for finfish populations where growth and reproductive output continue throughout adult life. Tanner crabs differ fundamentally because terminal molt permanently alters future growth trajectories. Once males become morphometrically mature, they cease growing. Consequently, maturity simultaneously affects reproductive potential; future legal biomass production; fishery yield; and vulnerability to fishing. *This creates a much tighter coupling between maturity and productivity than assumed in traditional SPR frameworks.* The implication is that mature biomass is not simply a measure of reproductive capacity; it is also a determinant of future fishery production. Current F35% calculations do not fully capture this relationship.

Maturity and Fishery Selectivity Are Not Aligned

A second concern is the disconnect between maturity and fishery vulnerability. Many morphometrically mature males remain below legal size and contribute substantially to the SPR calculation. However, these same individuals contribute little to current fishery production. Consequently, the population component driving F35% calculations is not identical to the population component driving fishery performance. This creates a fundamental conceptual problem. F35% is intended to reflect sustainable productivity, yet much of the biomass contributing to the reference point is effectively unavailable to the fishery.

Lack of Evidence Linking SPR to Recruitment

Perhaps the most important concern is the absence of a demonstrated stock-recruitment relationship. The biological rationale for F35% ultimately depends on the assumption that maintaining spawning potential contributes to future recruitment and productivity. However, the assessment materials provide little evidence that Tanner crab recruitment is strongly linked to spawning potential. Instead, recruitment appears to be heavily influenced by environmental variability, larval survival, and ecosystem conditions. Consequently, it is not clear that maintaining spawning potential at 35% of unfished levels has a biologically meaningful relationship to future recruitment outcomes.

In summary, for these reasons I conclude that F35% remains a useful management convention rather than a strongly biologically justified reference point. Its continued use is *acceptable in the near term, but I do not view it as the optimal long-term basis for Tanner crab management.*

TOR 3B: If not, can the reviewer provide more appropriate alternatives for reference points?

I do not recommend immediate abandonment of the current framework because management continuity is important and no alternative has yet been fully evaluated. However, I strongly recommend that alternative reference-point approaches be considered and investigated, including:

Alternative 1: Mature Male Biomass-Based Reference Points

The most obvious alternative would be to base management directly on mature male biomass rather than SPR. This approach would provide several advantages: (1) direct linkage to reproductive capacity; (2) direct linkage to fishery performance; (3) simpler biological interpretation; and (4) improved transparency for stakeholders. Unlike F35%, mature male biomass is directly observable and directly relevant to both mating potential and fishery yield. The primary challenge would be identifying biologically meaningful target and limit thresholds.

Alternative 2: Effective Reproductive Biomass

A more biologically realistic approach would focus on effective reproductive biomass rather than total mature male biomass. Such a metric could incorporate male size structure; shell condition; sex ratios; and mating success. This approach would better represent actual reproductive capacity than current SPR calculations. However, additional biological research would be required before implementation.

Alternative 3: Spatially Explicit Reference Points

The assessment materials provide increasing evidence for regional differences in productivity and maturity. If these patterns persist, future reference points may need to account for eastern productivity; eastern productivity; and localized depletion risk. A single coastwide reference point may become increasingly difficult to justify.

Alternative 4: MSE-Derived Harvest Control Rules

This is the alternative I would most strongly recommend. Rather than asking what level of SPR should be maintained, Management Strategy Evaluation could determine which harvest control rule (e.g., Heller-Shipley et al. 2021) best achieves management objectives. Potential objectives include maximizing long-term yield; maintaining reproductive capacity; minimizing collapse risk; reducing catch variability; and maintaining fishery stability. MSE would allow direct comparison of the current F35% framework against alternative approaches and would provide a far stronger scientific basis for future management decisions.

Overall, among the alternatives considered, MSE-based evaluation of biomass-oriented harvest control rules appears to offer the greatest potential for improving future Tanner crab management.

My Additional Comments on Empirical Harvest Control Rules and NOAA Fisheries–State Management Alignment

A major concern I have with the current Tanner crab reference-point framework is the discrepancy between the federal assessment structure and the State of Alaska's operational management strategy. The federal assessment treats eastern Bering Sea Tanner crab as a single stock and produces a single OFL and ABC, whereas the State of Alaska manages the fishery using separate east and west management areas divided at 166°W. This difference creates a practical disconnect between the biological scale of the federal reference points and the spatial scale at which harvest decisions are implemented. The spatial structure document explicitly notes this mismatch: federal management treats Tanner crab as a single stock, while the State sets separate TACs east and west of 166°W.

This mismatch is particularly important because the current F35% and B35% framework is largely model-derived, coastwide, and only indirectly connected to the empirical indicators used in fishery management. In contrast, state management decisions are more closely tied to observed survey abundance, legal male biomass, mature male biomass, recruitment pulses, fishery performance, and regional differences in stock condition. As a result, F35% and B35% may function more as federal accounting tools for OFL determination than as biologically meaningful or operationally central reference points for actual Tanner crab fishery management.

For this reason, I recommend that the assessment team and managers begin evaluating empirical harvest control rules as alternatives or complements to the current F35%/B35% framework. Empirical harvest control rules could be based directly on observable indicators such as legal male biomass, mature male biomass, female biomass, recruitment indices, regional survey trends, and size composition. These rules may be especially useful for Tanner crab because recruitment is episodic, maturity and fishery selectivity are not aligned, and spatial differences between eastern and western areas appear increasingly important.

I would like to recommend a possible empirical harvest control rule that could include three components: a threshold biomass below which directed fishing is closed, a ramped harvest rate that increases with mature or legal male biomass, and regional constraints to prevent disproportionate harvest from one area when the other area is weak. Such a rule would be simpler to explain, more directly linked to fishery performance, and more consistent with the way the State of Alaska currently manages east and west Tanner crab areas. However, it should not be adopted without simulation testing.

I recommend that alternative empirical harvest control rules be evaluated through MSE. Candidate rules should be tested against the current Tier 3 F35%/B35% approach under scenarios that include recruitment variability, survey catchability uncertainty, spatial structure, terminal molt dynamics, environmental nonstationarity, and hybridization. Performance metrics should include long-term yield, probability of overfishing, probability of falling below biomass thresholds, catch stability, regional depletion risk, and robustness to assessment error.

The development of empirical harvest control rules would also help reconcile differences between NOAA Fisheries assessment outputs and State of Alaska management strategies. NOAA Fisheries could continue to provide coastwide OFL and ABC advice required under the federal Tier system, while empirical rules could provide a transparent bridge to area-specific TAC setting. This would improve consistency between scientific advice and operational management without requiring immediate abandonment of the existing federal framework.

In the near term, I recommend retaining the current federal reference-point framework for OFL and ABC calculation but developing empirical harvest control rules in parallel for evaluation. In the medium term, if MSE demonstrates that empirical rules perform as well as or better than F35%/B35% rules, they should be considered as formal alternatives or supplements *to the current reference-point system. This would make Tanner crab management more transparent, more spatially responsive, and more directly linked to observable stock and fishery conditions.*

TOR 3C: Is morphometrically mature male biomass the appropriate metric for use in the harvest control rule?

Among currently available metrics, morphometrically mature male biomass remains the most appropriate metric for use in the harvest control rule. Unlike F35%, mature male biomass has a direct biological interpretation and is closely linked to both reproductive capacity and fishery performance. The metric also aligns well with the biology of Tanner crab because only males are harvested; mature males contribute directly to mating; terminal molt determines future fishery recruitment. Consequently, mature male biomass is arguably more biologically meaningful than the SPR metrics currently used to derive management reference points. However, the metric is not without limitations, including:

Mature Biomass Is Only a Proxy for Reproductive Capacity

Reproductive success depends on more than total mature male biomass. Other important factors include male size distribution; shell condition; spatial overlap with females; sex ratio; and mating behavior. Therefore, mature male biomass should be viewed as a practical surrogate rather than a direct measure of reproductive output.

Spatial Considerations

Increasing evidence of east-west population structure raises questions regarding whether coastwide mature male biomass adequately reflects reproductive potential throughout the stock. Future evaluations should consider whether spatially explicit biomass indicators are warranted.

Hybridization

If hybrid abundance continues to increase and hybrids contribute to reproduction, the interpretation of mature male biomass may eventually require revision.

Despite these limitations, no alternative metric currently provides a stronger combination of biological relevance, operational feasibility, and management utility. Therefore, morphometrically mature male biomass should remain the primary metric used in the Tanner crab harvest control rule.

I conclude that the current F35%/B35% reference-point framework remains operationally functional and can continue to support Tanner crab management in the near term. The framework is transparent, well established, and consistent with the broader BSAI crab management system. Furthermore, the assessment team demonstrated that current OFL and stock-status calculations are relatively robust to moderate changes in maturity estimation, providing confidence that existing management advice is not immediately compromised by the issues identified during this review. However, I find that the biological and management justification for continued reliance on F35% and B35% is substantially weaker than generally recognized. The conceptual foundation of SPR-based reference points is rooted in assumptions that may not be fully appropriate for Tanner crab biology. Terminal molt fundamentally alters the relationship between maturity, growth, productivity, and fishery yield. In addition, morphometric maturity and fishery selectivity are not aligned, such that a substantial portion of the biomass contributing to SPR calculations may have limited relevance to fishery performance.

The absence of a demonstrated stock-recruitment relationship further weakens the biological interpretation of maintaining spawning potential at a fixed proportion of unfished levels.

I also realized a growing disconnect between the federal assessment framework and operational fishery management. NOAA Fisheries' stock assessment and reference-point system are based on coastwide estimates of mature male biomass and SPR-derived reference points, whereas the State of Alaska manages the fishery through area-specific harvest strategies and TAC allocations that are more closely linked to observed abundance, legal male biomass, recruitment strength, and regional stock conditions. As evidence for spatial structure, divergent east-west productivity, and environmental nonstationarity continues to accumulate, this disconnect may become increasingly difficult to justify.

Taken together, these considerations suggest that the current reference-point system should be viewed as a practical management convention rather than a biologically optimal representation of Tanner crab productivity. While the existing framework remains suitable for near-term management, future assessment development should focus on identifying reference points and harvest control rules that are more directly linked to Tanner crab biology, fishery performance, and management objectives.

In summary, I would like to make the following general recommendations.

High Priority

- ***<u>Retain the Current Reference-Point Framework for Near-Term Management</u>***
  The current F35%/B35% framework should continue to be used for OFL and ABC calculations until alternative approaches have been rigorously evaluated. Abrupt replacement of the existing system is not warranted based on the information currently available.
- ***<u>Initiate a Formal Review of Alternative Reference-Point Frameworks</u>***
  The assessment team, Crab Plan Team, SSC, and management agencies should begin a formal evaluation of alternative reference points that are more directly linked to Tanner crab biology and fishery performance. Particular attention should be given to biomass-based reference points, effective reproductive biomass metrics, and alternative harvest control rules that are less dependent on SPR assumptions.
- ***<u>Conduct Management Strategy Evaluation (MSE) of Alternative Harvest Control Rules</u>***
  A comprehensive MSE should be conducted to compare the performance of the current F35%/B35% framework against alternative approaches. Candidate harvest control rules should include mature male biomass-based control rules; legal male biomass-based control rules; empirical indicator-based harvest rules; spatially explicit harvest control rules; and environmentally informed harvest strategies. Performance should be evaluated with respect to conservation, yield, fishery stability, resilience to recruitment variability, and robustness to assessment uncertainty.
- ***<u>Evaluate Empirical Harvest Control Rules</u>***
  Given the apparent disconnect between assessment reference points and operational management, empirical harvest control rules should receive particular attention. Such rules could be based directly on observable indicators including mature male biomass; legal male abundance; recruitment indices; regional survey trends; and fishery performance indicators. Empirical approaches may provide a more transparent and

biologically relevant bridge between federal assessment outputs and State of Alaska management decisions.

Medium Priority

- ***Investigate Spatially Explicit Reference Points and Harvest Strategies***
  Increasing evidence of east-west differences in abundance, productivity, maturity schedules, and recruitment suggests that coastwide reference points may not adequately represent regional biological conditions. The assessment team should evaluate whether spatially explicit reference points or area-specific harvest control rules would improve management performance and reduce localized depletion risk.
- ***Evaluate the Relationship Between Mature Male Biomass, Reproductive Capacity, and Fishery Performance***
  Additional research is needed to determine whether morphometrically mature male biomass remains the most appropriate measure of stock productivity and reproductive capacity. Alternative measures such as size-weighted mature male biomass, effective mating biomass, or reproductive-capacity indices should be investigated.
- ***Incorporate Environmental Diagnostics into Productivity Evaluation***
  The biological basis of current reference points assumes relatively stationary productivity relationships. Future work should evaluate whether environmental indicators such as bottom temperature, cold-pool extent, and climate-related distribution shifts influence stock productivity sufficiently to warrant adaptive management approaches.

Lower Priority

- ***Continue Evaluation of Hybridization Effects***
  Although current hybrid abundance does not appear sufficient to alter stock-status determinations, continued monitoring is warranted. If hybrids contribute substantially to future reproduction or recruitment, future reference-point calculations and harvest control rules may require modification.
- ***Periodically Reevaluate Reference Points as New Information Becomes Available***
  Reference points should not be viewed as static. As understanding improves regarding maturity dynamics, spatial structure, environmental variability, recruitment processes, and hybridization, the scientific basis of the current framework should be reassessed through periodic review.

In summary, I recommend retaining the current F35%/B35% framework as an interim management tool while initiating a structured transition toward evaluating more biologically meaningful and management-relevant alternatives. In particular, empirical biomass-based harvest control rules and MSE-tested management procedures offer considerable promise for improving alignment between stock assessment outputs, State of Alaska management strategies, Tanner crab biology, and long-term fishery objectives. Such efforts would strengthen the scientific foundation of Tanner crab management and improve its ability to respond to future ecological and fishery changes.

TOR 4. Two-Area Model

The question of spatial structure represents one of the most important strategic issues facing future Tanner crab assessment and management. Although the eastern Bering Sea Tanner crab stock is currently assessed as a single coastwide population, the State of Alaska manages harvest through eastern and western management areas separated at approximately 166°W longitude. This creates an unusual situation in which the assessment and management systems operate at different spatial scales.

Recent analyses presented during the review documented increasingly divergent eastern and western population dynamics, including differences in recruitment, maturity schedules, size structure, biomass trends, and environmental conditions. These findings raise an important question: not whether Tanner crab comprise two completely independent stocks, but whether the current single-stock assessment framework adequately represents a spatially structured population and provides appropriate management advice under changing environmental conditions.

Overall, I conclude that substantial evidence exists for biologically meaningful spatial structure. However, available information does not yet justify implementation of a fully operational two-area assessment model. Instead, the evidence supports a phased and adaptive approach involving enhanced spatial diagnostics, development of spatial operating models, and formal evaluation of management consequences before implementation of a two-area assessment.

TOR 4A: Under what circumstances would a two-area model for Tanner crab be recommended?

A two-area assessment model would be recommended if spatial processes are shown to materially influence assessment results, stock status determinations, or management performance. Importantly, the decision should not be based solely on evidence of spatial differences. Most marine populations exhibit some degree of spatial heterogeneity. The key question is whether those differences are large enough to affect management outcomes. I would like to recommend the following criteria to determine if a two-area model for Tanner crab is needed:

Criterion 1: Persistent Regional Differences in Productivity

The strongest justification for a two-area assessment would be evidence that eastern and western Tanner crab exhibit persistently different productivity regimes. Such evidence could include consistently different recruitment patterns; different maturity schedules; different growth trajectories; different natural mortality rates; and different responses to environmental conditions. The assessment team presented evidence that western recruitment has recently dominated stock growth while eastern abundance has generally declined. If such differences persist over multiple generations, a coastwide productivity assumption may become increasingly difficult to justify.

Criterion 2: Evidence of Management-Relevant Localized Depletion

A two-area model would also be warranted if coastwide stock indicators mask biologically important regional declines. For example: coastwide biomass could remain stable; eastern biomass could continue declining; and TACs could remain high because western biomass is increasing. Under such circumstances, the single-stock framework could fail to identify localized depletion risks. The possibility of localized depletion is particularly relevant because Alaska already manages harvest through separate eastern and western areas.

Criterion 3: Improved Management Performance

The strongest justification for a two-area model would be demonstration through simulation testing that spatial management performs better than the current coastwide framework. Performance metrics should include conservation risk; long-term yield; catch stability; regional depletion risk; and resilience to environmental variability. If MSE demonstrates improved performance of a two-area framework, implementation would be justified even if complete biological stock separation cannot be demonstrated.

Criterion 4: Climate-Driven Divergence

Evidence increasingly suggests that cold-pool dynamics and bottom temperature influence Tanner crab distributions. If climate change continues to generate divergent east-west productivity patterns, spatially explicit assessment approaches may become increasingly necessary regardless of stock structure.

In summary, I would recommend a two-area assessment model if spatial differences are shown to be persistent, management-relevant, and capable of influencing harvest outcomes. The strongest justification would come from demonstration that a spatial framework improves management performance rather than from stock-structure evidence alone.

TOR 4B: Are there any circumstances under which a two-area model would expressly not be recommended?

Yes. A two-area assessment should not be implemented solely because spatial differences are observed. If there exists the following evidence, I would recommend a two-area assessment model might be unnecessary.

Circumstance 1: High Connectivity

If future analyses demonstrate strong demographic connectivity between eastern and western regions, separate assessment units may create a false impression of independent population dynamics. Under such circumstances, separate models could generate misleading estimates of productivity and stock status.

Circumstance 2: Insufficient Data

Spatial models require substantially more information than coastwide models. Current uncertainties remain substantial regarding larval exchange; adult movement; regional productivity; area-specific selectivity; and regional recruitment dynamics. Implementation of a two-area model without adequate data would likely increase uncertainty rather than reduce it.

Circumstance 3: No Demonstrated Management Benefit

Additional model complexity is justified only if it improves management performance. If MSE demonstrates that a two-area assessment produces little improvement in conservation outcomes, yield, or stability, the added complexity would not be warranted.

Circumstance 4: Structural Uncertainty Exceeds Spatial Signal

At present, uncertainty associated with survey catchability, maturity estimation, recruitment variability, and natural mortality may exceed uncertainty associated with stock structure. If this remains true, efforts should focus first on resolving these higher-priority uncertainties.

In summary, I would conclude that a two-area model should not be implemented simply because spatial differences exist. Implementation should require evidence that spatial structure *materially affects management performance and that sufficient information exists to support reliable estimation of area-specific population processes.*

TOR 4C: Are there any data that could be gathered (or analyses performed with existing data) to inform this decision?

Yes. Several research priorities would substantially improve future evaluation of spatial assessment needs and approaches.

- ***Spatial Operating Model and MSE (highest priority)***
  The most valuable next step is not additional stock-structure analysis but development of a spatial operating model. Such a model would allow evaluation of coastwide management; area-specific management; alternative harvest strategies; and climate-driven spatial shifts. This would directly address the management consequences of spatial structure.
- ***Adult Movement Studies***
  Movement remains one of the largest uncertainties. Tagging studies could provide information regarding east-west exchange rates; seasonal movement patterns; connectivity among management areas.
- ***Larval Connectivity Analyses***
  Existing larval transport studies should be expanded. Particular attention should focus on source-sink dynamics; recruitment connectivity; environmental influences on transport.
- ***Spatial Assessment Diagnostics***
  Several analyses could be performed immediately using existing data. Examples include: east-west retrospective analyses; regional recruitment indices; regional maturity schedules; area-specific biomass trends; and regional projection analyses. These diagnostics could be incorporated into annual assessments even before implementation of a two-area model.
- ***Localized Depletion Analyses***
  I would strongly recommend evaluating whether coastwide harvest advice could result in localized depletion under realistic spatial scenarios. This issue may be more important than formal stock structure itself. A good understanding of fishing fleet dynamics is necessary to address this issue.
- ***Climate Vulnerability Analyses***
  Future work should evaluate cold-pool shifts; temperature-driven redistribution; and region-specific productivity responses. Such analyses may ultimately provide the strongest justification for spatial management.

In summary, I conclude that the most informative future work would focus on evaluating management consequences of spatial structure through operating models and MSE. Additional genetic studies alone are unlikely to resolve the central management question. The key issue is not whether eastern and western Tanner crab represent separate biological stocks, but whether spatial processes materially affect management performance.

I conclude that Tanner crab exhibit biologically meaningful spatial structure and are best described as a spatially structured metapopulation rather than either a homogeneous stock or two fully independent populations. Current evidence does not justify immediate implementation of a two-area assessment model. However, the current single-stock framework should not be viewed as the inevitable long-term solution. Continued divergence in regional productivity, *increasing environmental variability, and the mismatch between NOAA Fisheries' coastwide assessment and Alaska's area-based management system suggest that spatial processes will become increasingly important in future management. Accordingly, assessment development should proceed toward greater spatial representation through annual spatial diagnostics, spatial operating models, and MSE-based evaluation of alternative management strategies. The ultimate decision regarding a two-area assessment should be driven by improvements in management performance rather than by stock-structure evidence alone.*

TOR 5. Hybrid Snow-Tanner Crab

I believe that the rapid increase in Tanner–snow crab hybrids represents an important and potentially transformative biological developments identified during this review. Historically, hybrids constituted only a minor component of eastern Bering Sea survey catches and received little attention in assessment or management. Recent surveys, however, have documented unprecedented numbers of hybrids across multiple size classes and life-history stages. Although current assessment sensitivity analyses indicate limited effects on mature male biomass, OFLs, and stock-status determinations, the significance of hybridization extends far beyond its immediate impact on management quantities. The emergence of hybrids challenges fundamental assumptions regarding stock identity, productivity, reproductive dynamics, species distributions, and the long-term validity of existing assessment and management frameworks.

I therefore consider *hybridization not simply as an abundance-accounting issue, but as an emerging ecological and management issue with potentially important implications for future assessment and management of both Tanner crab and snow crab.*

TOR 5A: How should hybrid crab be treated in the assessment?

I agree with the assessment team's conclusion that hybrids should not currently be incorporated directly into the operational Tanner crab assessment. However, my reasoning differs somewhat from that presented by the assessment team. The principal reason hybrids should remain outside the operational assessment is not because their current abundance effects are small. Rather, it is because the biological processes governing hybrid dynamics and their possible interactions with Tanner crab and snow crab remain largely unknown. At present, there is insufficient information regarding fertility; reproductive success; growth rates; maturity schedules; natural mortality; recruitment contribution; and species assignment through time. Consequently, any attempt to model hybrids explicitly would require assumptions that are presently unsupported by empirical evidence.

However, I am concerned that the current assessment may be treating hybrids too narrowly as a bookkeeping issue. Hybridization has the potential to influence multiple assessment processes simultaneously. Hybridization could affect survey abundance estimates; maturity schedules; growth transitions; size composition patterns; stock structure interpretation; and productivity estimation. Current sensitivity analyses largely focus on abundance accounting and OFL effects. While useful, these analyses do not address broader biological and assessment consequences.

The increasing abundance of hybrids may represent a biological response to changing environmental conditions, including climate-driven shifts in species distributions. In this context, hybridization may provide valuable information regarding ecosystem change and should be treated as an ecological indicator rather than merely an assessment nuisance variable.

I recommend maintaining hybrids outside the operational assessment framework while continuing annual monitoring and expanded sensitivity analyses. However, hybrid abundance, distribution, and demographic characteristics should be routinely reported within future assessments as emerging indicators of ecosystem change and potential future assessment risk.

TOR 5B: How should hybrid crab be treated in the development of reference points and harvest control rules?

At present, hybrids should not be incorporated directly into reference-point calculations or harvest control rules. The primary reason is that there is currently no scientific basis for determining how hybrids contribute to reproductive capacity, productivity, or fishery sustainability. Reference points are intended to represent biological productivity and reproductive potential. However, for hybrids, virtually all of the quantities required for such calculations remain unknown. Specifically, we do not know whether hybrids are fertile; whether they successfully reproduce; whether they backcross with Tanner crab or snow crab; whether hybrid offspring survive and recruit; and whether hybrids exhibit different growth or mortality rates. Under these circumstances, direct incorporation into reference-point calculations would create an appearance of precision unsupported by biological evidence.

I also have a more fundamental concern. I believe the greater issue is not whether hybrids should be included in current reference-point calculations, but whether increasing hybridization may eventually undermine assumptions underlying the existing reference-point framework. Current biological reference points such as F35% and B35% calculations assume species identity is stable; reproductive output is species-specific; and productivity parameters are stationary. Large-scale hybridization could challenge all three assumptions. If hybrid abundance continues increasing, future reference-point evaluations may need to consider hybrid reproductive contribution; hybrid biomass; effective reproductive biomass across species; ecosystem-level productivity metrics. Such changes are not justified at present, but may become necessary in the future.

I recommend that hybridization should be incorporated into future Management Strategy Evaluation (MSE) exercises as an uncertainty scenario. The objective should be to determine whether increasing hybrid abundance could materially alter management performance under existing harvest control rules.

TOR 5C: Are there additional data streams that would be helpful to gather or experiments to be performed that would better inform how to treat hybrid crab in assessment and management?

Yes. In fact, I consider hybrid biology to be one of the high-priority research needs identified. Current uncertainty regarding hybrid dynamics is sufficiently large that it limits both assessment development and future management planning. The most important unanswered question is whether hybrids contribute to future recruitment. Research should determine fertility; mating success; reproductive output; and offspring viability. Without this information it is impossible to evaluate the contribution of hybrids to stock productivity. Current genetic sampling should be substantially expanded. Monitoring should evaluate hybrid prevalence; temporal trends; spatial distribution; backcrossing rates; and hybrid generation structure. This information is essential for determining whether hybridization represents an episodic phenomenon or a persistent demographic process. For growth and maturity studies, hybrid-specific estimates are needed for growth, maturity, size-at-terminal molt and mortality. These parameters are necessary before any future assessment incorporation can be considered. I also strongly recommend evaluating environmental drivers of hybridization. Particular attention should focus on bottom temperature, cold-pool dynamics, species overlap, and climate-related distribution shifts. Understanding these drivers may ultimately be more important than understanding hybrid abundance itself.

An emerging priority is ecosystem monitoring. Hybridization may represent a sentinel indicator of ecosystem reorganization under climate change. Consequently, hybrid monitoring should be integrated into broader ecosystem assessments rather than being treated solely as a fisheries issue.

In summary, I conclude that the current assessment team's treatment of hybrids is appropriate for immediate management needs. Hybrids should remain outside the operational Tanner crab assessment and should not currently be incorporated into reference-point calculations or harvest control rules. However, I disagree with any interpretation that hybridization is therefore of minor importance. On the contrary, hybridization may represent one of the most significant emerging biological issues facing eastern Bering Sea crab management.

The current management consequences appear modest largely because hybrid biology remains poorly understood, not because hybridization is biologically unimportant. I therefore view hybridization as a strategic uncertainty rather than a resolved issue. Accordingly, future assessment development should focus on understanding the demographic, reproductive, and ecological consequences of hybridization before evaluating whether changes to assessment models, reference points, or harvest control rules are warranted.

My prioritized recommendations are made below:

High priority research would include expanding genetic monitoring and hybrid identification programs, conducting reproductive viability and fertility studies, estimating hybrid-specific growth, maturity, and mortality parameters, and including hybridization scenarios in future MSE analyses.

Medium priority research would include evaluating environmental drivers of hybridization, incorporating hybrid indicators into annual assessment reporting, and developing exploratory hybrid population models.

Long-term priority would include reevaluating assessment treatment if hybrid abundance continues increasing, evaluating whether future reference-point frameworks should incorporate hybrid reproductive contribution, considering hybridization as part of broader climate-driven ecosystem assessment and management planning.

V. Conclusions and Recommendations

I would like to commend the Assessment Team for their efforts in conducting the eastern Bering Sea Tanner crab assessment. I was impressed by the breadth of expertise and experience of the team, the amount of effort spent collecting, processing and compiling the data, and the constructive and transparent discussions during the review.

I conclude that the assessment team has produced a scientifically rigorous assessment that continues to provide a defensible basis for management advice. Significant progress has been made in addressing key uncertainties and improving biological realism within the assessment framework. The review identified four overarching scientific themes that warrant continued attention:

- The increasing importance of spatial structure in Tanner crab population dynamics.
- Continued uncertainty regarding survey catchability and abundance scaling.
- The need to better understand relationships among growth, maturity, recruitment, and environmental variability.
- Emerging uncertainty associated with hybridization and climate-driven ecosystem change.

None of these issues currently undermine the validity of stock status determinations. However, they collectively indicate that future assessments should move toward more process-oriented approaches that explicitly account for spatial structure, environmental variability, and observation uncertainty. The Tanner crab assessment remains one of the strongest crab assessments currently conducted by the Alaska Fisheries Science Center. Continued development of GMACS, survey selectivity analyses, and spatial assessment approaches will further strengthen its scientific foundation and management utility.

Overall, I conclude that the eastern Bering Sea Tanner crab assessment remains scientifically robust and suitable for management use. None of the issues identified during this review undermine the validity of current stock-status determinations or management advice. However, the assessment is increasingly confronting challenges that cannot be fully addressed within a traditional single-stock, stationary-productivity framework. I, therefore, recommend retaining the current assessment and management framework in the near term while initiating a deliberate transition toward a more spatially explicit, uncertainty-aware, climate-informed, and management-oriented system. Particular emphasis should be placed on improving integration between federal stock assessment and State of Alaska management, developing empirical and MSE-tested harvest control rules, explicitly accounting for survey uncertainty, and evaluating the consequences of spatial structure and hybridization for future stock productivity and fishery performance. These efforts will provide a stronger scientific foundation for Tanner crab management and improve the resilience of the assessment system under future environmental and ecological change.

Detailed prioritized research commendations are detailed in each TOR. They can be distilled into a smaller set of strategic priorities that collectively address the most important scientific, assessment, and management challenges facing eastern Bering Sea Tanner crab. The overarching conclusion of my review is that future improvements will depend less on incremental refinements of existing model parameters and more on addressing structural uncertainties associated with spatial dynamics, survey observation processes, changing environmental conditions, and the connection between assessment outputs and management decisions.

The highest priority recommendation is the development of a spatial operating model and implementation of a comprehensive MSE framework. Multiple review topics, including spatial stock structure, reference points, federal-state management inconsistencies, and climate-driven distribution shifts, ultimately converge on the same question: does the current management system continue to perform adequately under increasingly heterogeneous biological and environmental conditions? MSE provides the most rigorous mechanism for evaluating alternative harvest control rules, spatial management approaches, and climate-responsive strategies before they are implemented. Such a framework would allow managers to evaluate tradeoffs among conservation, yield, fishery stability, and localized depletion risk while explicitly accounting for uncertainty.

A second major priority is improving understanding and treatment of survey catchability uncertainty. The side-by-side selectivity study demonstrated that observation uncertainty may be as important as traditional sources of uncertainty such as recruitment, growth, or natural mortality. Future research should focus on estimating absolute gear efficiency, evaluating environmental influences on catchability, and propagating catchability uncertainty through stock assessments, projections, and OFL calculations. Improved understanding of the survey observation process is likely to generate substantial improvements in abundance estimation and assessment reliability.

A third priority is modernization of the biological reference-point and harvest-control-rule framework. The review concluded that the current F35% and B35% reference points function more as management conventions than biologically validated measures of stock productivity. Tanner crab biology, particularly terminal molt and the disconnect between maturity and fishery selectivity, weakens the biological interpretation of SPR-based reference points. Future work should evaluate alternative biomass-based and empirical harvest control rules, particularly those based on mature male biomass, legal male biomass, or other directly observable indicators. Such approaches may provide a more transparent and biologically meaningful basis for management while improving consistency between federal assessments and state management practices.

The review also identifies spatial population dynamics as a critical area for future research. Although evidence does not currently support implementation of a two-area assessment model, increasing divergence between eastern and western regions suggests that spatial processes are becoming increasingly important. Future work should focus on adult movement studies, larval connectivity analyses, regional productivity estimates, localized depletion risk, and climate-driven changes in distribution. Understanding connectivity and spatial productivity will help determine whether more spatially explicit assessment and management approaches are warranted in the future.

Another emerging priority concerns hybridization between Tanner crab and snow crab. I recognize hybridization as one of the most novel and potentially consequential biological developments affecting the stock. Although hybrids should not currently be incorporated into operational assessments or reference-point calculations, substantial uncertainty remains regarding their fertility, reproductive contribution, growth, mortality, and ecological significance. Future research should focus on genetic monitoring, reproductive studies, and environmental drivers of hybridization. Hybrid abundance may ultimately serve as an important indicator of ecosystem change and climate-driven shifts in species interactions.

Finally, I would like to emphasize the need to strengthen integration between federal stock assessment and State of Alaska management. One of the strongest themes emerging from the review is the mismatch between NOAA Fisheries' coastwide assessment framework and Alaska's east-west management structure. Future assessment development should focus on producing information that is directly relevant to management decisions, including regional biomass indicators, area-specific projections, spatial diagnostics, and evaluation of regional harvest strategies. Better alignment between assessment outputs and management implementation will improve transparency, increase stakeholder confidence, and enhance the long-term effectiveness of Tanner crab management.

In summary, I recommend shifting future research priorities from refining individual assessment parameters toward addressing broader structural questions regarding spatial dynamics, observation uncertainty, biological reference points, climate change, hybridization, and management performance. Collectively, these efforts would move the Tanner crab assessment toward a more spatially explicit, climate-informed, uncertainty-aware, and management-oriented framework capable of supporting sustainable fisheries under increasingly complex ecological conditions. Continued investment in these research and monitoring priorities is strongly warranted. Advancing toward a process-based, spatially resolved, and ecosystem-informed assessment framework will be essential to ensure the long-term sustainability and resilience of the East Bering Sea Tanner crab fishery under changing environmental conditions.

VI. References

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Kruse, G. H., Daly, B. J., Fedewa, E. J., Stram, D. L., & Szuwalski, C. S. (2025). Ecosystem-based fisheries management of crab fisheries in the Bering Sea and Aleutian Islands. *Fisheries Research*, *281*, 107236.

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Tamone, S. L., Taggart, S. J., Andrews, A. G., Mondragon, J., & Nielsen, J. K. (2007). The relationship between circulating ecdysteroids and chela allometry in male Tanner crabs: evidence for a terminal molt in the genus Chionoecetes. *Journal of Crustacean Biology*, *27*(4), 635-642.

Weems, J. (2024). *Early Life Biology and Ecology of King and Tanner Crabs in the Bering and Chukchi Seas*. University of Alaska Fairbanks.

VII-1. Appendix 1: Bibliography of materials provided for review

Materials provided for the 2026 eastern Bering Sea Tanner crab stock assessment review

Working papers

- BSAI Crab SAFE Introduction, September 2025
- Stockhausen, W.T. 2026 Tanner Crab Assessment Considerations
- Stockhausen, W.T. 2026. **Tanner crab Stock Structure and Spatial Considerations**
- Stockhausen, W.T. 2026. Addendum to Transition from TCSAM02 to GMACS: 1 function call
- Stockhausen, W.T. 2026. Description of the Tanner Crab Stock Assessment Model, Version 2
- Stockhausen, W.T., 2018. Stock assessment and fishery evaluation report for the tanner crab fisheries of the Bering Sea and Aleutian Islands regions. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2018 Final Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK. https://www.npfmc.org/wp-content/PDFdocuments/resources/SAFE/CrabSAFE/2018/SAFE_2018_Complete.pdf.
- Stockhausen, W. T. 2026. Side-by-Side Survey Catchability Studies: Cooperative Research to Estimate Survey Catchability for Tanner Crab in the Eastern Bering Sea DRAFT.
- NOAA Technical Memorandum NMFS-XXX-##
- Zacher, L.Z., S. M. Hennessey, J. I. Richar, E. J. Fedewa, E. R. Ryznar, and M. A. Litzow. 2026. The 2025 Eastern and Northern Bering Sea Continental Shelf Trawl Surveys: Results for Commercial Crab Species. NOAA Technical Memorandum NMFS-AFSC-513

○ VII-2. Appendix 2: Statement of Work for Dr. Yong Chen

Performance Work Statement (PWS)
National Oceanic and Atmospheric Administration (NOAA)
NOAA Fisheries
Center for Independent Experts (CIE) Program
External Independent Peer Review

1.

Review of Eastern Bering Sea Tanner Crab Assessment
June 9 - 11, 2026

Background

NOAA Fisheries is mandated by the Magnuson-Stevens Fishery Conservation and Management Act, Endangered Species Act, and Marine Mammal Protection Act to conserve, protect, and manage our nation's marine living resources based upon the best scientific information available (BSIA). NOAA Fisheries science products, including scientific advice, are often controversial and may require timely scientific peer reviews that are strictly independent of all outside influences. A formal external process for independent expert reviews of the agency's scientific products and programs ensures their credibility. Therefore, external scientific peer reviews have been and continue to be essential to strengthening scientific quality assurance for fishery conservation and management actions.

Scientific peer review is defined as the organized review process where one or more qualified experts review scientific information to ensure quality and credibility. These expert(s) must conduct their peer review impartially, objectively, and without conflicts of interest. Each reviewer must also be independent from the development of the science, without influence from any position that the agency or constituent groups may have. Furthermore, the Office of Management and Budget (OMB), authorized by the Information Quality Act, requires all federal agencies to conduct peer reviews of highly influential and controversial science before dissemination, and that peer reviewers must be deemed qualified based on the OMB Peer Review Bulletin standards[1].

Scope

The goal of this review is to gain external expert review and input on several issues with respect to the Bering Sea and Aleutian Islands Tanner crab assessment, including:

1. transition of the Tanner crab assessment to the Generalized Model for Assessing Crustacean Stocks (GMACS) framework,
2. methodology for incorporation of data collected in side-by-side selectivity experiments into the Tanner crab assessment,
3. the appropriateness of currently used reference points for Tanner crab (and potential alternatives),

[1] https://www.whitehouse.gov/wp-content/uploads/legacy_drupal_files/omb/memoranda/2005/m05-03.pdf

4. the feasibility and need for development of a two-area model for Tanner crab
5. how to treat hybrid snow/Tanner crab in the assessment and management process

External expert review for this stock is necessary and timely because Tanner crab abundance is currently increasing strongly and hybridization with snow crab has reached levels not historically observed. If these trends continue, Tanner crab may become a larger part of the portfolio of fished crab stocks in the Bering Sea than it has been for the past several decades. External review will help ensure the science used in the management of Tanner crab continues to be robust and transparent in the pursuit of management advice that maximizes long-term sustainable catches.

The specified format and contents of the individual peer review report are found in **Annex 1**. The Terms of Reference (ToRs) of the peer and review are included in **Annex 2**. The tentative agenda of this virtual panel review and process review meetings is included in **Annex 3**.

Requirements
NOAA Fisheries requires three reviewers to conduct an impartial and independent peer review in accordance with this Performance Work Statement (PWS), OMB Guidelines, and the ToRs below. Modifications to this Performance Work Statement (PWS) and ToRs cannot be made during the peer review, and the Contracting Officer's Representative (COR) and the CIE contractor shall approve any modifications prior to the peer review. All ToRs must be addressed in each reviewer's report.

Effective review of the issues of concern requires reviewers with several specific skillsets. In-depth experience with the implementation and behavior of *integrated size-structured assessment models* that have complex internal dynamics and are fit to numerous data sources is needed to appropriately review the Tanner crab model. Experience in the *management of crustaceans* is needed to support the analysis and discussion of reference points and harvest control rules. Finally, knowledge of *crustacean biology* is needed given the distinct structure of Tanner crab population dynamics and the resulting implications for management.

The chair, who is in addition to the panel of three reviewers, will not be provided by the CIE. Although the chair will be participating in this review, the chair's participation (e.g., labor and travel) is not covered by this contract.

Tasks for Reviewers
Each CIE reviewer shall complete the following tasks in accordance with the PWS and Schedule of Milestones and Deliverables herein.

Pre-review Background Documents: Two weeks before the peer review, the NOAA Fisheries Project Contact will send (by electronic mail or make available at an FTP site) to the CIE reviewers the necessary background information and reports for the peer review. In the case where the documents need to be mailed, the NOAA Fisheries Project Contact will consult with the CIE on where to send documents. The CIE reviewers are responsible only for the pre-review documents that are delivered to the reviewer in accordance with the PWS scheduled deadlines specified herein. The CIE reviewers shall read all documents in preparation for the peer review.

Documents to be provided to the CIE reviewers prior to this review include:

Documents for review (links to come):

- Document describing issues for which input is needed
- 2025 Tanner Crab Assessment
- May 2026 Preliminary Tanner crab models and other analyses

Background information:

- Survey tech memo
- previous MSE work (BSFRF, UW, ADFG, AFSC)
- State TAC docs
- Chionoecetes mortality papers
- Hybrid crab background

Panel Review Meeting: The CIE reviewers shall conduct the independent peer review in accordance with the PWS and ToRs and shall not serve in any other role unless specified herein. The CIE reviewers shall attend and actively participate in a professional and respectful manner as members of the meeting review panel, and their peer review tasks shall be focused on the ToRs as specified herein. The NOAA Fisheries Project Contact is responsible for any meeting arrangements (e.g., conference room reservations, video conferencing logistics, etc.).

Chair Summary Report: The reviewers shall assist the Chair of the meeting with contributions to the summary report. Reviewers are not required to reach a consensus.

Contract Deliverables - Independent CIE Peer Review Report: The CIE reviewers shall complete an independent peer review report in accordance with this PWS. The CIE reviewer shall complete the independent peer review according to required format and content as described in **Annex 1**. The CIE reviewer shall complete the independent peer review addressing each ToR as described in **Annex 2**. The tentative agenda of the panel review meeting is attached in **Annex 3**.

Foreign National Security Clearance

When reviewers participate during a panel review meeting at a government facility, the NOAA Fisheries Project Contact is responsible for obtaining the Foreign National Security Clearance approval for reviewers who are non-US citizens. For this reason, the reviewers shall provide requested information (e.g., first and last name, contact information, gender, birth date, passport number, country of passport, travel dates, country of citizenship, country of current residence, and home country) to the Project Contact for the purpose of their security clearance, and this information shall be submitted at least two weeks in advance. For additional information, please see the following link: https://www.commerce.gov/osy/programs/foreign-access-management. All CIE reviewers must have a REAL ID-compliant form of identification to access Federally owned or leased facilities The contractor is required to use all appropriate methods to safeguard Personally Identifiable Information (PII).

Place of Performance
The place of performance shall be the Alaska Fisheries Science Center, Seattle, WA.

Period of Performance
The CIE reviewers' duties shall not exceed **14** days to complete all required tasks.

Schedule of Milestones and Deliverables
The contractor shall complete the tasks and deliverables in accordance with the following schedule:

Schedule	Milestones and Deliverables
Within two weeks of award	Contractor secures participation of the CIE reviewers.
At least two weeks prior to the panel review meeting	Pre-review documents are provided to the reviewers.
June 9 - 11, 2026	The reviewers participate and conduct an independent peer review during the panel review meeting.
Approximately 2 weeks later	Contractor receives draft reports
Within 3 weeks of receiving draft reports	Contractor submits final reports to the Government

* The Peer Review Summary Report will not be submitted to, reviewed, or approved by the Contractor.

Applicable Performance Standards
The acceptance of the contract deliverables shall be based on three performance standards: (1) The reports shall be completed in accordance with the required formatting and content in **Annex 1**; (2) The reports shall address each ToR as specified **Annex 2**; and (3) The reports shall be delivered as specified in the schedule of milestones and deliverables.

Travel
All travel expenses shall be reimbursable in accordance with Federal Travel Regulations (Travel resources | GSA), and all contractor travel must be approved by the COR prior to the actual travel. Any travel conducted prior to the receipt of proper written authorization from the COR

will be done at the Contractor's own risk and expense. International travel is authorized for this contract. Travel is not to exceed $12,000.00.

Confidentiality and Data Privacy
This contract may require that services contractors have access to Privacy Information. Services contractors are responsible for maintaining the confidentiality of all subjects and materials and may be required to sign and adhere to a Non-disclosure Agreement (NDA).

NOAA Fisheries Project Contact:
Cody Szuwalski
Research fisheries biologist
AFSC/NMFS/NOAA
7600 Sand Point Way, Seattle, WA, 98115
cody.szuwalski@noaa.gov

Annex 1: Peer Review Report Requirements

1. The CIE independent report shall be prefaced with an Executive Summary providing a concise summary of the findings and recommendations as specified in the ToR.

2. The main body of the reviewer report shall consist of a Background, Description of the Individual Reviewer's Role in the Review Activities, Summary of Findings for each ToR in which the weaknesses and strengths are described, and Conclusions and Recommendations in accordance with the ToRs.

   a. Reviewer should describe in their own words the review activities completed during the panel review meeting, including providing a brief summary of findings, of the science, conclusions, and recommendations.

   b. Reviewer should discuss their independent views on each ToR even if these were consistent with those of other panelists, and especially where there were divergent views.

   c. Reviewer should elaborate on any points raised in the Summary Report that they feel might require further clarification.

   d. The CIE independent report shall be a stand-alone document for others to understand the weaknesses and strengths of the science reviewed, regardless of whether or not they read the panel summary report. The CIE independent report shall be an independent peer review of each ToRs and shall not simply repeat the contents of the summary report.

3. The reviewer report shall include the following appendices:

   Appendix 1: Bibliography of materials provided for review
   Appendix 2: A copy of the CIE Performance Work Statement
   Appendix 3: Panel Membership or other pertinent information from the panel review meeting.

Annex 2: Terms of Reference for the Peer Review

Review of Eastern Bering Sea Tanner Crab Assessment

CIE reviewers are contracted to complete their independent peer review based on the ToRs. Therefore, the CIE-NOAA Fisheries review and approval process is based on whether the CIE independent reports addressed each of the ToRs.

1. Generalized Model for Assessing Crustaceans Stocks (GMACS)
    a. Comment on the pros and cons of transitioning from the status quo bespoke assessment to the GMACS framework.
    b. Are there any concerns with the GMACS framework that would preclude its adoption?
    c. If so, are there clear paths to addressing these concerns (and what are the paths)?
2. Side-by-side selectivity
    a. Are the methods presented for estimating the selectivity of the NMFS survey gear based on the side-by-side experiments scientifically sound?
    b. Are the resulting changes in the scale of the population when incorporating the side-by-side data into the assessment defensible and appropriate for providing management advice?
    c. If not, how would the reviewer approach the provision of management advice using assessment output that incorporates the selectivity experiment data?
3. Reference points
    a. Are F35%-based reference points appropriate for Tanner crab in light of terminal molt and the discrepancy between maturity and selection in the fishery?
    b. If not, can the reviewer provide more appropriate alternatives for reference points?
    c. Is morphometrically mature male biomass the appropriate metric for use in the harvest control rule?
4. Two area model
    a. Under what circumstances would a two-area model for Tanner crab be recommended?
    b. Are there any circumstances under which a two-area model would expressly not be recommended?
    c. Are there any data that could be gathered (or analyses performed with existing data) to inform this decision?
5. Hybrid snow/Tanner crab
    a. How should hybrid crab be treated in the assessment?

b. How should hybrid crab be treated in the development of reference points and harvest control rules?

c. Are there additional data streams that would be helpful to gather or experiments to be performed that would better inform how to treat hybrid crab in assessment and management?

Reviewers must provide details on the basis of their responses to the review questions.

Annex 3: Tentative Agenda for the eastern Bering Sea Tanner crab assessment

June 9-11, 2026

Chair: Cody Szuwalski (cody.szuwalski@noaa.gov)

Agenda: Eastern Bering Sea Tanner Crab Assessment CIE Review

Dates: June 9–11, 2026
Chair: Cody Szuwalski (NOAA Fisheries)
Location: Alaska Fisheries Science Center, Seattle, WA

June 9, 2026

Time Topic Presenter
9:00–9:30 Welcome, objectives, and review process overview Szuwalski
9:30–12:00 Introduction to Tanner crab assessment and overview of GMACS transition Stockhausen
13:00–14:00 Survey data description and survey methodology Kodiak team
14:00–15:00 Catch data description and fishery context Jackson
15:00–17:00 Initial reviewer requests

June 10, 2026

9:00–11:00 Report back on CIE requests (model structure, GMACS implementation)
Stockhausen
11:00–12:00 Hybrid snow/Tanner crab: treatment in assessment and management
Stockhausen
13:00–14:30 Reference points (F35%, alternatives, and harvest control rules)
Szuwalski
14:30–16:00 Side-by-side selectivity experiments and integration into assessment
Stockhausen
16:00–17:00 Spatial structure of population and fishery Stockhausen
17:00–17:30 Discussion and identification of final requests

June 11, 2026

9:00–12:00 Report back on CIE requests that involved model runs and additional analyses
Stockhausen
13:00–15:00 Panel discussion: synthesis, strengths, weaknesses, and recommendations
15:00–17:00 Wrap up and next steps

Annex 4. Individual Independent Peer Reviewer Report Requirements

1. The independent Peer Reviewer report shall be prefaced with an Executive Summary providing a concise summary of whether they accept or reject the work that they reviewed, with an explanation of their decision (strengths, weaknesses of the analyses, etc.).

2. The report must contain a background section, description of the individual reviewers' roles in the review activities, summary of findings for each TOR in which the weaknesses and strengths are described, and conclusions and recommendations in accordance with the TORs. The independent report shall be an independent peer review, and shall not simply repeat the contents of the Peer Reviewer Summary Report.

   a. Reviewers should describe in their own words the review activities completed during the panel review meeting, including a concise summary of whether they accept or reject the work that they reviewed, and explain their decisions (strengths, weaknesses of the analyses, etc.), conclusions, and recommendations.

   b. Reviewers should discuss their independent views on each TOR even if these were consistent with those of other panelists, but especially where there were divergent views.

   c. Reviewers should elaborate on any points raised in the Peer Reviewer Summary Report that they believe might require further clarification.

   d. The report may include recommendations on how to improve future assessments.

3. The report shall include the following appendices:

Appendix 1: Bibliography of materials provided for review
Appendix 2: A copy of this Performance Work Statement
Appendix 3: Panel membership or other pertinent information from the panel review meeting.

Annex 5. Peer Reviewer Summary Report Requirements

1. The main body of the report shall consist of an introduction prepared by the Research Track Peer Review Panel chair that will include the background and a review of activities and comments on the appropriateness of the process in reaching the goals of the peer review meeting. Following the introduction, for each assessment /research topic reviewed, the report should address whether or not each Term of Reference of the Research Track Working Group was completed successfully. For each Term of Reference, the Peer Reviewer Summary Report should state why that Term of Reference was or was not completed successfully. It should also include whether they accept or reject the work that they reviewed, with an explanation of their decision (strengths, weaknesses of the analyses, etc.)

   To make this determination, the peer review panel chair and reviewers should consider whether or not the work provides a scientifically credible basis for developing fishery management advice. If the reviewers and peer review panel chair do not reach an agreement on a Term of Reference, the report should explain why. It is permissible to express majority as well as minority opinions.

   The report may include recommendations on how to improve future assessments.

2. If any existing Biological Reference Points (BRPs) or BRP proxies are considered inappropriate, include recommendations and justification for alternatives. If such alternatives cannot be identified, then indicate that the existing BRPs or BRP proxies are the best available at this time.

3. The report shall also include the bibliography of all materials provided during the peer review meeting, and relevant papers cited in the Peer Reviewer Summary Report, along with a copy of the CIE Performance Work Statement.

   The report shall also include as a separate appendix the assessment Terms of Reference used for the peer review meeting, including any changes to the Terms of Reference or specific topics/issues directly related to the assessments and requiring Panel advice.

VII-3. Appendix III: List of Participants

- William Stockhausen, NOAA
- Cody Szuwalski, NOAA
- Grant Adams, NOAA
- Sandra Lowe, NOAA
- Melissa Haltuch, NOAA
- Mike Litzow, NOAA
- Jim Ianelli, NOAA
- Cole Monnahon, NOAA
- Tyler Jackson, ADFG
- Katie Palof, ADFG
- Yong Chen, CIE
- Martin Cryer, CIE
- Larry Jacobson, CIE