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TO: Gulf of Mexico Fishery Management Council
FROM: Steve Cadrin, Independent Reviewer
DATE: April 1, 2021
RE: **Peer Review of "The Great Red Snapper Count: Estimating the Absolute Abundance of Red Snapper in the U.S Gulf of Mexico"**

In consultation with the Gulf Council, I reviewed the report "The Great Red Snapper Count: Estimating the Absolute Abundance of Age-2+ Red Snapper (*Lutjanus campechanus*) in the U.S. Gulf of Mexico" (Stunz et al. 2021). The primary objective of the review was to determine if the abundance estimate and its variance are reliable and consistent with data and population characteristics by addressing three specific terms of reference. In addition to addressing the specific terms of reference, general comments are provided on the case study and its application for stock assessment. The peer review process is being conducted in association with the Council's Standing Scientific and Statistical Committee (SSC), Special Reef Fish SSC, and Special Socioeconomic SSC (March 30 to April 2, 2021 via webinar), but my consultation is not a formal component of the Scientific and Statistical Committee's recommendations on an overfishing limit and acceptable catch.

The Stunz et al. (2021) report was distributed to reviewers on March 3, 2021. Reviewers and Council staff met with Dr. Stunz on March 10 2021 for a general presentation of the report and preliminary technical discussion. The meeting identified the need for more technical information on the analytical design. In response, a revised report was distributed on March 15 that included more information, primarily in additional appendices (e.g., Stunz 2016, Ahrens et al. 2021, Siders 2021). I appreciate the timely response and additional information. A draft review was submitted for distribution on March 23, and discussed with principal investigators, SSC members and others at the Standing, Reef Fish, and Socioeconomic SSC Meeting, March 30 – April 2, 2021. Some technical details of this review were revised based on the SSC discussion, but the draft conclusions were confirmed.

As some background, I have experience in a variety of stock assessment methods, including collaborative field work with fishermen to estimate absolute stock size, integrated assessments that incorporate such information, and providing recommendations on acceptable catch. For disclosure, I was an external reviewer for Mississippi-Alabama Sea Grant proposals for 2016 Red Snapper Experimental Design for Population Estimates in the Gulf of Mexico Region, the 2017 Phase I Red Snapper Experimental Design Workshop, and the 2017 Phase II Implementation Plan Review Panel. I also served as a reviewer and Working Group member for several stock assessments Southeast Data, Assessment, and Review (SEDAR) process. For example, I am a member of the SEDAR 74 Red Snapper Stock Identification Working Group, providing my general experience in stock identification rather than expertise in red snapper biology or fisheries. I am not an expert on red snapper biology or Gulf of Mexico fisheries, so my review of this project relies on the 2018 benchmark stock assessment (SEDAR 2018) and previous SEDAR assessments (SEDAR 2005, 2009, 2013; Cass-Calay et al. 2015) as the regional peer review processes' determination of best scientific information available to evaluate consistency with 'population biological characteristics'.

Terms of Reference

1. Study Design and Sampling Approaches
2. Statistics and Data Analysis
3. Results

Terms of Reference Background: *The Great Red Snapper Count (GRSC) study provides an absolute abundance estimate of age 2+ red snapper in the U.S. waters of the Gulf of Mexico. The primary objective of the review is to determine whether the absolute abundance estimate and its variance is reliable and consistent with input data and population biological characteristics. The review is divided into three parts and specifically does not address the tagging components of the GRSC.*

In summary of my technical review, I compliment Dr. Stunz and his collaborators on an impressive implementation of a large-scale field study that applies advanced sampling technologies in collaboration with fishermen to provide an absolute estimate of stock size for a valuable fishery. I expect that the project's results will be a valuable resource for understanding red snapper, other reef fishes and their fisheries, and the data will be mined for a variety of applications.

The stratified design is rational for meeting the stated objectives, but the a-priori sampling design could not be implemented, because the sampling frame was poorly defined. Deviations from the sampling design, post-stratification and extensive extrapolation were needed to account for large areas of uncharacterized bottom, strata with low visibility or high red snapper densities. These revisions to the initial design were necessary to adapt to local constraints and conditions, but they impose some biases and tend to underestimate variance.

Paired observations with optic and acoustic sampling technologies suggest that acoustic detectability is much less than optic detectability. Therefore, the detection efficiency of acoustic sampling technology appears to be much less than 100%, as assumed in the analysis. Accordingly, estimates of abundance in western strata, which were primarily based on acoustic sampling, may be substantially underestimated.

The estimate of abundance is substantially greater than those from the SEDAR52 stock assessment, which may reflect uncertain scaling in the assessment, and the difference may decrease when recreational catch is increased in the assessment. However, estimates of red snapper are much more evenly distributed between the eastern and western regions than estimates of abundance by area from the SEDAR52 assessment. This difference in perceived spatial distribution may result from different sampling designs, sampling technologies and estimation methods among regions (e.g., underestimation of abundance in western strata from acoustic methods).

Estimates of variance do not account for substantial sources of uncertainty, because several important aspects of the estimation were assumed to be deterministic (e.g., detection efficiency, imputed density for unsampled strata, species composition, age at length, acoustic signal processing, area swept, …) and considerable sources of uncertainty in the estimation process were not accounted for in the variance estimate (e.g., number of artificial reefs off Mississippi, post-stratification, sensitivity to alternative post-stratifications, …).

From my perspective, based on the information provided in the report, estimates of abundance can be considered in an integrated stock assessment. However, the estimate of stock-wide abundance cannot be used directly for stock assessment because regional estimates do not appear to be comparable or additive. The estimated variance of the population estimate may be substantially underestimated and is not reliable for statistical weighting in an integrated stock assessment. The most appropriate integration of the abundance estimates may be to include abundance estimates in eastern regions (with a more credible variance) in the spatially-structured stock assessment and to consider estimates of abundance in the western regions as a lower bound constraint in the assessment model.

Term of Reference 1. Study Design and Sampling Approaches - *Evaluate study design used for developing a composite estimate of absolute abundance by habitat type, depth, region, and age.*

As determined in Phase II of the project, a single sampling method was not capable of estimating red snapper abundance estimates in each habitat type in the northern Gulf of Mexico, so the use of multiple sampling methods that apply advanced technologies were encouraged. Phase II of the project also recognized that habitat mapping was not sufficient for accurately stratifying the northern Gulf by habitat type, but further mapping was explicitly excluded in the project solicitation. Although the challenges of sampling diverse habitats were met by developing and applying state-of-the-art technologies, the large area of uncharacterized habitat in the northern Gulf posed a major source of uncertainty that is difficult to quantify.

<u>1.a. Assess the sufficiency of spatiotemporal sampling by study strata</u>

As recommended by Phases I and II of the project, the experimental design was stratified, and stratification was hierarchical (Stunz 2016), based on a-priori strata defined by

i. region (aligning with state jurisdictions: Texas, Louisiana, Mississippi/Alabama, Florida),
ii. depth strata within regions (10-40, 40-100, 100-160m),
iii. habitat type strata within the shallowest three depth strata (artificial reef, natural reef, uncharacterized bottom) defined using available habitat maps.

However, the a-priori sampling design could not be implemented as planned, because the sampling frame could not be well defined, and uncharacterized bottom was heterogeneous.

The a-priori stratification was revised in several ways for estimating abundance:

- Uncharacterized bottom was further stratified based on probability of occupancy by red snapper, and samples were post-stratified for estimating abundance.
- The region of Florida was subdivided into five sub-regions (Figure 5), and the four depth strata off Florida (Figures 2-4) were combined into two depth strata (10-50 and 50-160 m).
- The Mississippi/Alabama region was stratified into three differently defined depth strata for artificial reefs (18-37, 37-55, 55-91 m).
- Some artificial reef strata were further stratified by size categories of red snapper (small, medium, large, extra-large).
- Artificial reef strata in the Texas region were further stratified by size (large and small).
- Pipelines were an additional sampling stratum, and those strata were sampled differently than other artificial reef habitats and sampled with transects with random starting locations.
- The sample design for uncharacterized bottom strata was revised because of local constraints and conditions, and density samples were 'post-hoc aligned with the appropriate strata':
    - Samples from the northern shallow low-probability stratum off Florida were used to represent the northern mid-depth low-occurrence stratum.
    - Samples from the northern mid-depth high-probability stratum off Florida were used to represent the northern deep high-occurrence stratum.
    - Data from sampled strata in the Mississippi/Alabama region were used to represent shallow strata and the deep high-probability stratum.
- Some strata were not sampled, and mean density was imputed from adjacent strata. For example, some strata in artificial reef and shallow-depth strata in the Louisiana region were not sampled and were represented by samples in adjacent Texas strata.

Sample selection within strata was random within many strata (e.g., Figure 5 shows randomly selected locations within Florida strata; sampling within uncharacterized bottom strata were at random locations), but non-random in others (e.g., Figures 14, 17 and 18 depict nonrandom transects across depth strata off Texas). The basis of sample allocation among strata were not described, but it appears that sample allocation to strata varied among and within regions. For example, the deepest stratum off Mississippi/Alabama had the least sampling effort because of cost. Stratified estimates were based on stratum area or number of structures.

The sampling frame of artificial reef strata off Mississippi/Alabama region was not well defined. The entire region was stratified by depth, but the sampling grids in the Alabama Artificial Reef Zone only cover about half of the region (Figure 8). Surveys of western Alabama waters outside the zone were used to derive the number of unpublished reefs off coastal Mississippi, but the number of snags reported by bottom trawl surveys suggest that there are more artificial reefs off coastal Mississippi.

Two post-stratification schemes (random stratified and ratio estimator) were applied to estimate stock-wide abundance. Post-stratification was based on two-stage adaptive sampling. Post-strata were defined by predictive models of red snapper occurrence as a function of environmental predictor variables using 14 datasets (Siders 2021, Appendix D). Then, post-strata were representatively sampled by the surveys funded by the project.

The resulting sampling design was a mix of stratified random (for most strata), probability-based location sampling (Florida strata and uncharacterized bottom strata in other regions), and depletion sampling (in artificial reef strata off Mississippi/Alabama). Although these sampling designs may be suited for the conditions in each stratum type, they each have fundamentally different potential biases and statistical properties. Therefore, estimates of abundance and variance from each stratum may not be directly comparable or additive for a stock-wide abundance estimate (see notes on 1.e. calibration, below).

<u>1.b. Does heterogeneity in sampling by strata affect estimates of absolute abundance and variance around that estimate?</u>

Although the experimental design was stratified, the sampling design was not stratified random (as assumed in the analytical design; see section 2.a., below). The initial sampling design required modifications, including independent sampling among regions and strata. Density estimates were based on optic transects in Florida strata and Mississippi/Alabama natural reef strata. Abundance in artificial reef strata off Mississippi/Alabama was based on optic transects and depletion studies to account for double counting fish in high densities. A combination of optic and acoustic methods was used to sample strata in the western regions and along pipelines where visibility was poor. For example, optic sampling was used to derive species composition, and acoustic sampling was used to derive density in Texas strata. Similar to the different stratifications within regions, the independent sampling methods in each region have different potential biases and statistical properties. Therefore, estimates of abundance and variance from each stratum may not be directly comparable or additive for a stock-wide abundance estimate (see notes on 1.e. calibration, below).

<u>1.c. Evaluate assumptions and biases inherent to the design, and the directionality of those biases</u>

Section II.C.3. (sampling biases) discusses potential biases and their expected direction on the abundance estimate. The report concludes that the estimate of abundance is probably underestimated. Although some of the potential biases are positive, and many of the potential biases apply differently to the independent sampling designs and technologies in each region, I agree that the stock-wide estimate of abundance may be an underestimate.

The primary source of uncertainty was the assumption that all age-2+ red snapper were fully detectable by the optic and acoustic sampling technologies. Any lack of detection (e.g., from low visibility, high density, presence of congeners, acoustic 'dead zones' near the bottom and artificial structures) would bias the counts to be lower than the true values. Paired observations of optic and acoustic sampling indicates that acoustic detection is much less than 100% (see 1.e. calibration, below), suggesting that abundance is substantially underestimated in western strata where acoustic sampling was applied (Texas and Louisiana).

The design assumed that red snapper were not attracted to sampling devices or did not avoid them. Any avoidance (e.g., by large red snapper) would bias counts low, and attraction would bias counts high. Behavioral experiments (see 1.f, below) suggest that red snapper are not attracted or repelled by the sampling gear.

The design also assumed that the sampling frame included all occupied habitats in the northern Gulf. If some of the stock is outside the sampling frame (e.g., in habitats deeper than 91 m off Mississippi/ Alabama and 160m in other regions), the abundance estimate is biased low. Optic surveys suggest that red snapper occur in habitats beyond the sampled strata (e.g., deep salt dome and pinnacles on the continental slope).

The revised stratifications may have increased precision at the expense of some additional bias. For example, the length of pipelines and number of artificial reefs are uncertain and may have led to extrapolating beyond the intended habitat strata or included uncharacterized bottom in pipeline or reef strata. Surveys of western Alabama waters outside the Alabama Artificial Reef Zone were used to derive the number of unpublished reefs off coastal Mississippi, but the number of snags reported by bottom trawl surveys suggest that there are more artificial reefs off coastal Mississippi.

Video counts off Mississippi/Alabama were based on the MaxN protocol (i.e., deriving count from the maximum number of fish in a single frame during the viewing interval). Schobernd et al. (2014; cited in report but not listed in references) concluded that MaxN may produce biased estimates of abundance, and the mean count performed better in simulation. The report states that MaxN produces a conservative estimate of abundance because all fish are assumed to be in the image, but assuming the maximum count for the area may not be conservative in all conditions.

Other sources of bias include exclusion of statistical outliers, exclusion of small fish, spatial autocorrelation, and environmental conditions. Some observations of extremely high density were considered to be outliers and removed from the abundance estimate. The SSC presentation and discussion indicated that one outlier had large influence on the resulting abundance estimate.

Red snapper smaller than 250mm total length were removed from the analysis, which may have removed some age-2 fish from the abundance estimate. Samples were assumed to be independent, and image processing attempted to minimize autocorrelation, but some spatial autocorrelation among adjacent observations may have persisted. Hypoxia may have negatively influenced counts in some nearshore strata.

<u>1.d. Are sampling approaches collectively appropriate for determining an estimate of absolute abundance for red snapper in the Gulf?</u>

Although the sampling methods were appropriate for the regional conditions, they have substantially different detection probabilities (see section 1.e. calibration, below) and potential biases (see 1.c. biases, above). Therefore, estimates of abundance assuming 100% detection are not directly comparable or additive for deriving a stock-wide abundance estimate.

1.e. Are different sampling techniques effectively calibrated to each other for generating the absolute abundance estimate?

Paired samples of optic and acoustic technologies off Florida offer information on relative detection of the two technologies. Observed densities were weakly correlated (r=0.4), suggesting that the true observation error is much greater than the 11% CV derived by the stratified estimate. Density estimates from optic sampling were 9.1 times greater than those from acoustic sampling, suggesting that the assumption of 100% detection for both technologies is invalid. Revised analyses of paired observations presented at the SSC meeting that have refined assumptions of area sampled by each gear suggested that optic sampling were approximately four times greater than those from acoustic sampling

Model diagnostics for the depletion studies in Mississippi/Alabama artificial reef strata are not provided to evaluate how well catchability is estimated from the depletion samples. Results from the depletion experiments could help to evaluate the assumption of 100% detection of acoustic methods in other strata.

1.f. Are the biases and limitations of each approach effectively addressed?

Sampling protocols were designed to minimize biases, but some considerable biases remain (see 1.c. biases, above). Behavioral experiments were conducted off Florida to test attraction to or avoidance of the three mobile sampling gears utilized among Gulf regions. Minimal positive or negative behavioral reaction was observed displayed.

Term of Reference 2. Statistics and Data Analysis - *Evaluate the statistical methods used to analyze the data, and to construct the absolute abundance estimate and its variance*.

Phase II of the project specified a target coefficient of variation (CV) of 30%, which is realistic for a field survey of a fishery resource.

2.a. Is the statistical variance appropriate for habitat-specific, regional and Gulf-wide estimates?

The analytical design assumed simple random sampling within strata to derive stratum means and variances, and stratum statistics were combined to derive stratified mean and variance. However, the samples were not collected with a stratified random design. The implemented sampling was a mix of stratified random (for most strata), probability-based location sampling (Florida strata and uncharacterized bottom strata in other regions), and depletion sampling (in artificial reef strata off Mississippi/Alabama). Some observations were autocorrelated and not truly independent observations.

Arithmetic stratum means and variances are unbiased estimators, but descriptive diagnostics (e.g., statistical distributions of observations within strata, relative frequency of zero-count observations, strata with all zero-count observations?) were not provided in the report to determine if arithmetic means were appropriate for the application. Some observations of extremely high density were considered to be outliers and removed from the abundance estimate, which suggests that alternative estimators could be more efficient and better suited to the distribution of observation errors (e.g., Pennington 1983, Tu 2006).

2.b. Are potential sources of uncertainty effectively incorporated into variance estimates?

Estimates of variance do not account for substantial sources of uncertainty. Several important aspects of the estimation were assumed to be deterministic (e.g., detection efficiency, imputed density for unsampled strata, species composition, age at length, acoustic signal processing, area swept, …) when they also had considerable uncertainty. Other sources of uncertainty in the estimation process were also not accounted for in the variance estimate (e.g., number of artificial reefs off Mississippi, post-stratification, sensitivity to alternative post-stratifications, …).

At the SSC meeting, Dr. Stokes explained that observation error increases variance estimates, but those proofs assume that measurement error is white noise (i.e., measurement errors have a mean of zero), but several of the measurement errors may not involve white noise. For example, the 100% detection assumption implies that there were zero red snapper in acoustic 'dead zones'. So, any red snapper in that zone, and variability of density in that zone make the estimate of variance less than the true variance.

The two post-stratification schemes produced similar estimates (within 4.9 million or 4.4%). However, these are not technically independent estimates or replicates, because they are derived from the same data. This 4.4% is a measure of sensitivity to the post-stratification method and is not included in the 11% CV measure of precision within a model. Therefore, variance of the population estimate may be substantially underestimated.

Stratified sampling with a high frequency of zero-count observations and low replication from over-stratification tends to produce underestimates of variance (Tu 2006). At the extreme, strata with all zero-count observations have an estimated stratum variance of zero, and these strata decrease the estimate of stratified variance. However, these zero-count observations within the habitat of red snapper are not representative of the low (but non-zero) density in the stratum or the variance in the stratum. Stratum statistics presented at the SSC meeting included 17 of 54 strata (31%) that had mean density=0 variance=0 (two of the zero-strata had 0 stratum size). Those zero-strata do not contribute to the stock-wide abundance estimate but they have considerable influence on the stratified variance. These strata include red snapper habitat, so the true density and variance are greater than zero, and the zero-stratum results from low densities that are below the detection limits of the sampling technologies.

<u>2.c. Are imputations made for unsampled regions appropriate, and what are the potential implications for the direction of biases in the estimates?</u>
Some strata were not sampled, and mean density was imputed from adjacent strata. For example, some strata in artificial reef and shallow-depth strata in the Louisiana region were not sampled and were represented by samples in adjacent Texas strata. Although such imputation may be the best approach to address the unsampled strata, the imputation is not accounted for in the estimation of variance, so the estimate of precision is biased low.

The large extent of uncharacterized bottom required extensive extrapolation, with low ratios of sampled units to total units. These low sample ratios should produce low estimates of precision.

Term of Reference 3. Results - *Is the estimate and its variance reliable, consistent with input data and population biological characteristics, and useful as an estimate of absolute abundance of age 2+ red snapper?*
The estimate of age-2 red snapper abundance in late 2019 was 110 million with a CV of 11%. If the CV is correct, abundance estimates are appropriately reported in significant digits of 10-million. Because of the large area of uncharacterized habitat, those strata contributed the most to the stock-wide abundance estimate. As reported in section II.F.2.c (estimate reconciliation) the estimate of abundance is substantially greater than contemporary estimates from the SEDAR52 stock assessment. The stock-wide estimate of age-2+ abundance is about four times greater than the projected 2019 abundance and greater than estimates of unfished stock abundance from the SEDAR52 stock assessment (Figure 1. below; SEDAR 2018; age-2+ estimates and projections from M. Smith).

The report explains that a large portion of the estimated abundance is from uncharacterized bottom that is not targeted by red snapper fisheries and not well indexed by fishery-independent surveys in the stock assessment. However, if there is a large refuge from fishing, age composition samples should suggest a relatively low mortality rate, unless there is limited movement among fishing grounds and the refuges. Section II.D (tagging) reported that the average movement was 1-3 km, which should provide some mixing among adjacent habitats. Apparently, the assessment will be revised with increased estimates of recreational catch, which are expected to increase the stock assessment's estimate of abundance.

The estimated spatial distribution of the resource is relatively even (53% eastern regions, 47% western regions), which is substantially different than the spatial distribution estimated by the SEDAR52 assessment (21% eastern area, 79% western area; Figure 1). Stock assessments are typically better at assimilating data and estimating relative stock status than they are at estimating absolute stock size, but the different perspectives of spatial distribution raises concerns that the apparently even spatial distribution may result from unequal sampling efficiencies of the different sampling methods used in each region. Most hard bottom was in the Florida strata, sampled with optic methods, but most oil and gas platforms were in western region, sampled with acoustic methods. Estimates of abundance assumed 100% detection, but paired comparisons show that acoustic sampling has much lower detection. Therefore, abundance in western regions may be substantially underestimated, and including them in an integrated stock assessment may impose conflicting information on scale.

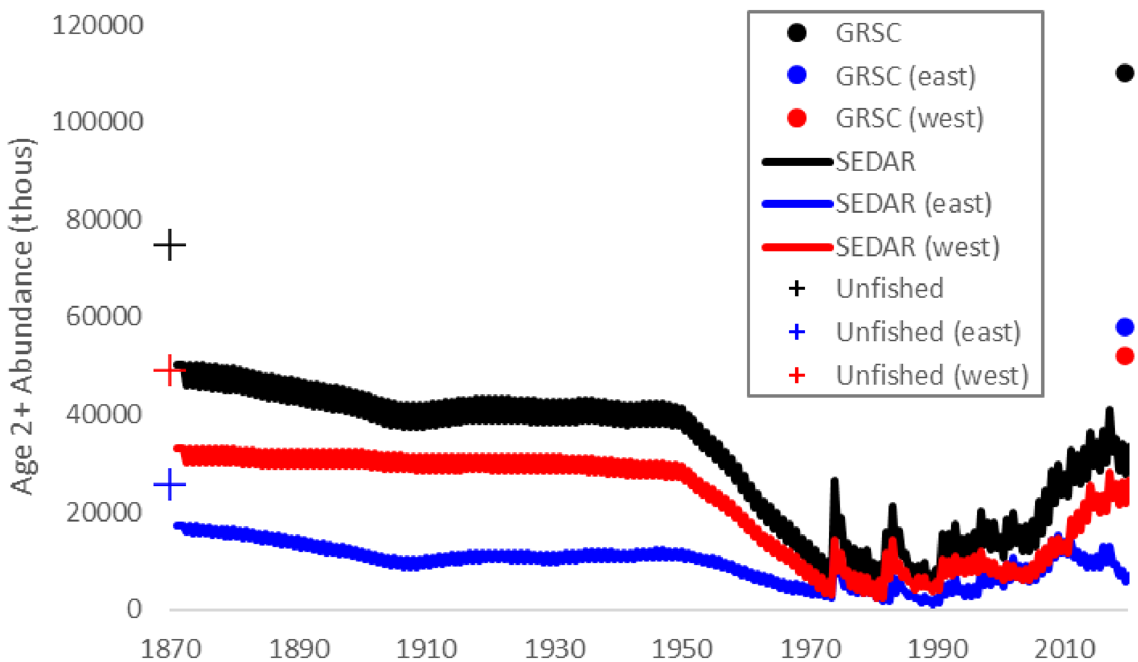

Figure 1. Red snapper abundance in the eastern and western areas of the northern Gulf of Mexico estimated from the Great Red Snapper Count (GRSC) and the SEDAR52 stock assessment (SEDAR 2018; unfished, 1870-2016 estimates, 2017-2020 projections at the overfishing limit).

3.a. Assumptions and biases inherent to the methods

Assuming 100% detection bias may have substantially underestimated abundance in western regions (see 1.e. calibration, above).

The relatively low CV despite the sampling challenges (e.g., heterogeneous habitats, visibility, high densities, patchy distributions) suggests that the variance estimate does not account for major sources of uncertainty and post-stratification (see 2.b. variance, above). Estimates of variance do not account for substantial sources of uncertainty, because several important aspects of the estimation were assumed to be deterministic, and considerable sources of uncertainty in the estimation process were not accounted for in the variance estimate. Paired samples of optic and acoustic technologies off Florida offer information on relative detection of the two technologies. Observed densities were weakly correlated (*r*=0.4), suggesting that the true observation error is much greater than the 11% CV implied by the stratified estimate. Therefore, variance of the population estimate may be substantially underestimated, and the estimate of variance is not reliable for application in risk-based catch advice or an integrated stock assessment.

3.b. Are assumptions made appropriate, given study design considerations?
Deviations from the a-priori sampling design were apparently necessary because of uncertain sampling frames and field conditions. However, these deviations from the design impose some biases and tend to underestimate variance.

3.c. Describe the magnitude and directionality of any biases
Section II.C.3. (sampling biases) discusses potential biases and concludes that the estimate of abundance is probably underestimated. I agree that the stock-wide estimate of abundance may be an underestimate (see 1.c. biases, above).

3.d. Can the data presented be combined with age-specific composition information for generating an age-specific estimate of abundance?
The estimate of stock-wide abundance cannot be used to derive an age-specific estimate of abundance, because regional estimates do not appear to be comparable or additive (see 1.e. calibration, above).

General Comments

Although the primary objective of the review was focused on the terms of reference to determine if the abundance estimate and its variance are reliable, this review offers the opportunity for more general perspectives on the scientific contribution and application to fishery management. Despite the limitations of the study detailed in the report and in my review, the project is an impressive case study in fisheries science that demonstrates value of an independent estimate of abundance based on collaborative fieldwork with fishermen and advanced technologies. The intense preparation, planning, and implementation, involving dozens of scientists, students, and fishermen serve as models for future large-scale case studies. The regional scope is rare but comparable to other large and successful investments in the assessments of southern bluefin tuna, Pacific halibut, and Atlantic sea scallops.

From my perspective, based on the information provides, the estimate of stock-wide abundance cannot be used directly for stock assessment because regional estimates do not appear to be comparable or additive. The most appropriate application may be to include abundance estimates in eastern regions (Tables 5 and 6) with a more credible variance in the spatially-structured assessment and to consider estimates of abundance in the western regions as a lower bound constraint in the assessment model.

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