SEDAR 46 U.S. Caribbean Data-Limited Species Assessment
Center for Independent Experts (CIE) Independent Peer Review Report

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1 Executive Summary

- The general approach taken for the data limited assessment, testing management procedures using random projections of the fishery, is the best scientific approach currently available. The method is, in essence, a decision analysis where the decision is encoded into the management procedures, and the performance of the management procedure is measured against management requirements.
- Even without further work, the methodology has identified alternate management procedures which outperform current management procedures. However, further work is required before the assessments could be considered able to identify an optimum management procedure.
- The approach can be further improved so that the set of possible management procedures that meet all criteria are more clearly identified and that all performances considered relevant are measured and reported.
- Improvements include more performance indicators or adaptation of current performance indicators to offer target or objective for management. (F/FMSY),
- The random parameter set used for the projections need to take better account of information and knowledge. Random draws of parameters are taken from independent parametric probability density functions, but alternative ways to generate joint parameter probability density functions should be considered. This would help identify the best management procedure for each fishery.
- I recommend fitting operational model parameters used for the MSE projections to the available data, generating a random draw of these parameters from a formal Bayesian posterior probability density. This may be possible using new software (e.g. mc-stan.org) for these data limited fisheries. This will condition the MSE simulations on observations and will make projections more realistic. An illustrative fit is provided in Appendix 4.

2 Background

This is one of three independent reports that describes the findings and conclusions of the review workshop for the SEDAR 46 U.S. Caribbean Data-Limited Species Assessment in accordance with the Center for Independent Experts (CIE) statement of work (Appendix 2). The National Marine Fisheries Service's (NMFS) Office of Science and Technology coordinates and manages a contract providing external expertise to conduct independent peer reviews of NMFS scientific projects without conflicts of interest. Each reviewer contracted by the CIE provides an independent peer review report to be approved by the CIE Steering Committee (www.ciereviews.org). In addition to the three independent CIE reports, there is a Review Panel summary report which represents the consensus view for all five panel members.

SEDAR 46 is a compilation of data, an assessment of the stocks, and CIE assessment review conducted for Caribbean Data-limited Species. A Data Workshop (DW) and Assessment Workshop (AW) were conducted 2-6 November 2015 in San Juan, Puerto Rico, with follow-up webinars in December 2015 and January 2016 to finalize the assessment. These Workshops produced a report and other material for the Review Workshop (RW), which took place 23-25 February 2016. The review panel is ultimately responsible for ensuring that the best possible assessment is provided through the SEDAR process. The stocks assessed through SEDAR 46 are within the jurisdiction of the Caribbean Fisheries Management Council and the territorial waters of Puerto Rico and the U.S. Virgin Islands.

3 Description of the Individual Reviewer's Role in the Review Activities

I conducted an independent peer review in accordance with the Statement of Work (Appendix 2) and Review Panel Terms of Reference.

Two weeks before the review workshop, the NMFS Project Contact made available the necessary background information and reports for the peer review. I subsequently attended the review workshop (RW), which took place 23-25 February 2016 in Miami, Florida. Results were presented at the RW of applying the DLMtool (Carruthers et al. 2014) and the mean length estimator for six species-island units selected by the SEDAR 46 Data/Assessment Workshop Panel. During the workshop, the Review Panel requested some additional analyses, which included changes to several of the base operating models (stock, fleet, and observation components) and also additional sensitivity analyses. The results of those analyses are presented in an addendum to the main report.

As a member of the Review Panel, I contributed to a separate summary of the Review Workshop, which was a consensus report of the entire panel. In accordance with the Statement of Work, the findings, conclusions and recommendations of this independent review report do not necessarily represent the views of other members of the Review Panel.

To see whether new Markov chain Monte Carlo software would be useful to condition management strategy evaluations (MSE) on the data available for these data-limited fisheries, I carried out a Bayesian fit of the operating model to the data typically available from these fisheries. A simplified age-structured operating model was fitted to St. Croix spiny lobster fishery data (catch, abundance indices, length compositions) to generate a joint random draw of all parameters conditional on these data. These results were used as the basis for making recommendations on further assessment work for these stocks. The majority of this work was done after the panel review workshop. The main results of this analysis are presented in Appendix 4.

4 ToR 1: Evaluate the data used in the assessment, including discussion of the strengths and weaknesses of data sources and decisions, and consider the following:

a. Are data decisions made by the DW and AW sound and robust?
b. Are data uncertainties acknowledged, reported, and within normal or expected levels?
c. Are data applied properly within the assessment model?
d. Are input data series reliable and sufficient to support the assessment approach and findings?

The decisions made by the DW and AW have been sound and robust. Summary information on each stock, strengths and weaknesses in the data and management is excellent. The stocks from the region used to test the approach are well chosen and illustrate the range of fisheries being managed.

Data uncertainties are acknowledged and well reported in the supporting documents. Some uncertainties exceed "normal" levels for some types of data. For example, total catches for some species are not considered reliable (under reported), whereas length compositions are sampled independently and, where they are available, are considered to represent the size composition of the landings reasonably well. The uncertainties in the data are understood, and have limited previous analyses. The current assessment approach is a response to this.

The available information is used correctly in the assessment models. Information is based on expert opinion, and includes the best available scientific information for these fisheries, including life history, selectivity and abundance. However, there could be significant improvements in the way the information is provided to the MSE operating model used for the projections. The way information is incorporated into the MSE model is informal and does not necessarily provide an accurate representation of likely parameter values.

It would seem unlikely that island populations constitute single stocks in terms of their recruitment. For example, spiny lobster is considered, at least from a population genetics point-of-view, a single Caribbean-wide stock, at least for the Northern Caribbean. Separate stock assessments including a stock recruitment relationship on a small island would be stretching credulity to its limits. Therefore, a spawner-per-recruit approach to reference points to define overfished and overfishing would be most appropriate. For the projection, highly random recruitment around a mean (very high steepness) would likely apply, but the overfished status would still depend on the spawning stock biomass ratio to the unexploited level. In the longer term, greater co-operation between US and UK Virgin Islands, and between Puerto Rico and the Dominican Republic in stock assessment and management may be appropriate for some of these fisheries.

Data collection remains poor for these fisheries. Data limited approaches did not hide the fact that with poor or insufficient data, it is not possible to manage fisheries well in the longer term. Any proposed management procedure should encourage more and better data to support the procedure, its implementation and further research so that management can be improved.

I believe that data could be used more efficiently and objectively in a Bayesian model to generate the random parameter draws used for the projections. This would combine the subjectivity for the initial parameter estimates with objectivity of the available observations. Perhaps more importantly, it would provide a joint parameter probability density which should eliminate any unintended and unrealistic projections within the MSE, and biases these may produce. This would improve the performance evaluation of the management procedure (MP) and provide a link between the data-limited methods and full stock assessment.

5 ToR 2: Evaluate and discuss the strengths and weaknesses of the methods used to assess the stock, taking into account the available data, and considering the following:

a. Are the data-limited methods scientifically sound and robust?
b. Are the methods appropriate given the available data?
c. Are the data-limited models configured properly and used in a manner consistent with standard practices?
d. Are the quantitative estimates produced reliable? Does the method produce management metrics (e.g. MSY, ABC, ACL) or other indicators (e.g. trends in F or Z, probability of overfishing) that may be used to inform managers about stock trends and conditions?

The data-limited methods are scientifically sound and robust, and appropriate given the available data. The analytical team justified their approach based on management strategy evaluation methods, which was correct. But the underlying theory for this approach is statistical decision analysis (Berger 1993), in various guises has been widely used for fisheries assessment (e.g. Punt and Hilborn 1997; Peterman et al. 1998). The focus is on making optimal decisions under risk rather than point estimates of stock status. This addresses uncertainty explicitly.

In this case, the decisions are encapsulated in the management procedures (MP), which decide how catch quotas are set in accordance with US fisheries management standards. The ABC should take into account risk in achieving the MSY objective, so the MP should really be deciding how the ABC, rather than the OFL, is set. It is worth noting that even in data rich stock assessments, an MSE approach is probably best practice, as stock assessments can never provide very accurate estimates. There are always significant uncertainties with interpretation of the data and limits on the useful information data may contain.

Given the data limited situation for these fisheries, the method is appropriate. The method is designed to take full and explicit account of uncertainty and risk. This is particularly useful for fisheries with limited data, where uncertainty is a dominant feature of the decisions.

The models were configured correctly. It is not clear that, given this was a new tool, any particular practice could be considered standard, but the application followed was justified and appeared sound.

The primary assessment method reviewed here was designed to test methods for producing quantitative estimates of management metrics to inform managers, not actually produce those metrics. Therefore, the objective of these analyses is not to inform managers about stock condition. If determination of stock status is an absolute requirement, significant improvements in data collection will be required.

The assessment identified management procedures which might produce the most reliable metrics to inform managers on their decisions. There is little evidence that the management metrics produced by the data limited methods will be accurate, but they should be robust to uncertainty.

The actual operation of the DLMtool software was obscure. Some characteristics of the software are unclear to me, so how these affect the performance statistics is also uncertain. In many cases, the only way to check the software is to examine the code. R code can be very dense, so it is difficult to identify issues without running the software itself. More clear documentation would help improve this package.

The models were used correctly. However, more diagnostics for the MSE would be useful for future reviews to check the simulations were not too unrealistic, or biased towards certain scenarios. Currently, the DLMtool appears to have significant runs with very high biomass. This could favour less risk averse MPs even though these scenarios are highly unlikely.

There is an opportunity to favour particular MPs when setting up MSE by supplying accurate information to them which in reality does not exist or is highly uncertain. In this case, any MP supplied with unbiased and precise data during the MSE will perform well. In reality, data may be biased and very imprecise. This was recognised by the analytical team, but left some of the output from the MSE giving a very optimistic assessment of some MPs that were never going to be appropriate in practice.

The five performance measures (including the short term yield measure) seem reasonable. They are binary and qualitative, indicating whether or not a management procedure meets a requirement on each random run. Like medians, these measures are robust and are unaffected by outliers and extreme values. A very small change might be to alter the criterion so that the probability that the stock is “above” rather than “equal to or above” biomass at MSY as more appropriate as a definition of not being in the overfished state.

The long-term (and short-term) yield criterion was difficult to achieve for many of the methods. This may be partly because of bias in the projection (favouring high biomass), but also within data-limited fisheries, it is difficult to imagine guaranteeing meeting this criterion without better information to set the appropriate catch limits.

6 ToR 3: Consider how uncertainties in the assessment, and their potential consequences, are addressed.

- Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods.
- Ensure that the implications of uncertainty in technical conclusions are clearly stated.

Uncertainty is captured through parametric probability density functions defined for model parameters and simulated observations. These parameters have been estimated for each species or have been generally accepted as being reasonable estimates through expert consensus (DW and AW). The consensus is based on experience for these and other similar stocks in the region.

The MSE emphasises the uncertainty by drawing parameters and observations from a wide range of possible values. Although some parameter combinations chosen at random may be unrealistic, the method tests procedures to evaluate the stock management and does not estimate real world catch limits or fishery status. Therefore, the evaluation should be robust to these additional uncertainties. While this is preferable compared to underestimating uncertainty, it is still better to try to match uncertainty to their true levels to improve advice.

The parameters are drawn from uniform and log-normal probability densities. While the uniform is generally considered uninformative, the choice of the range and the scale on which the uniform is set is informative on a parameter. For example, uniform probability for both asymptotic length (L_∞) and the growth rate (K) will imply something more is known about K compared to L_∞ because K is used in the growth model on an exponential scale. The log-normal may introduce positive bias dependent on implementation. These effects should be small and should not necessarily influence these results, but it is another reason to check diagnostics for the MSE runs or try to condition stochastic simulations better on the available data.

The implications of uncertainty are clearly stated and captured in the reported performance indicators. However, this could be enhanced as more criteria are identified. For example, a primary concern of stakeholders is likely to be whether catch limits might be significantly reduced below current levels. The probability of this happening (e.g. probability catches are reduced to <75% of the mean for years 2000-2015) could be estimated and reported if the projections are conditioned on past observations.

7 ToR 4: Consider the research recommendations provided by the Data and Assessment workshops and make any additional recommendations or prioritizations warranted.

- Clearly denote research and monitoring that could improve the reliability of future assessments.
- Provide recommendations on possible ways to improve the SEDAR process.

7.1 Data

The DW and AW identify important improvements to data collection and the assessment. I would support all their recommendations as they would improve the reliability of future assessments. However, I would prioritize the following work:

- Develop abundance indices, both fishery dependent and independent, for all fisheries. Abundance indices are important for monitoring stock size, and implementing the most reliable MPs.
- Obtain catch-at-length by gear to help estimate selectivity, which could improve length based estimators. This should include evaluation of discarding and its effects on landings. For example, larger hogfish may be discarded because of concerns with ciguatera.
- Productivity Susceptibility Analysis (PSA) might be used to identify indicator species, which could form the focus of data collection and management to protect a fishery on species groups. PSA is useful for identifying stocks which are vulnerable to overfishing. PSA will not provide reliable estimates of depletion.

Improving estimates and recording of total catches should also be recommended. While the MPs that meet the requirements do not require total catch, effective implementation of catch limits will do so.

I would also recommend considering sex ratios for protogynous species as a possible index proxy for stock status instead of mean length or CPUE. This may be easier to record for a number of species and may be more robust if information on growth is poor.

It is also important to note that more monitoring data will always improve management. Data-limited approaches do not overcome a lack of data; they are designed to make the best use possible of limited data. This has often meant increasing the number of assumptions and constraints on the stock assessment model, which tends to underestimate the uncertainty and limits the model diagnostics available.

7.2 Modeling

The DLMtool takes a step back from treating data-limited methods as stock assessments and test these simple models as management procedures within an MSE. This is a much better approach as it properly takes into account uncertainty, and allows the procedures to be evaluated. However, while the resulting MPs are less likely to cause overfishing, they will still likely miss fishing opportunities if data collection is not improved.

Full documentation for the DLMtool should be provided, particularly for the operating model. Although information on the models was available, it was difficult to find and to follow in its current form.

Of the recommendations provided for the MSE modelling by the AW, adding control implementation error (e.g. TAC overages) to the MSE is probably the most important. Although the other recommendations may improve MSE model accuracy, I suspect they would in practice make little difference to the majority of results.

More generally, the DLMtool software could be enhanced by allowing random parameters to be provided to the models rather than simple parametric probability density functions. This would allow greater freedom to account for relationships among parameters (e.g. multivariate densities), and to use alternative complex density functions based on likelihood (e.g. MCMC) or sampling theory (e.g. empirical bootstrap).

The DLMtool should offer alternative operational models to cover different life history characteristics of stocks. Specifically, sex differentiation in growth, and protogynous or protandrous hermaphroditism could be covered. Sex differences for many of these fisheries may be more important than size specific natural mortality.

The concept behind DLMtool is the same as for FLR (http://flr-project.org) – to create an environment for testing management procedures using MSE. FLR is more complex in the sense that it allows age structured stock assessment models. However, the operating model would likely be similar. It may be worth looking at the objects created by FLR rather than reinvent more objects to do the same task. Although there may be an argument to keep the DLMtool simple, as indicated by recommendations here, there will always be pressure to create more complex operating models, so using standard compatible objects as far as possible would be preferable.

7.3 SEDAR Process

The SEDAR is a rigorous review process, which is laudable. However, given this assessment presented a work in progress, it may have been possible to conduct this review remotely based on the materials provided to the workshop alone. A full review workshop could then have been conducted once the method had been completed. This could then also have been used to endorse specific MPs for specific fisheries.

Clearly measurable objectives for the fisheries being managed would be valuable. A major problem with these sorts of review processes is the lack of clarity provided by managers as to what the fisheries objectives are. Without these, it is difficult to propose a full set of performance indicators or make sure that all information useful to managers is reported. In this case, the analytical team addressed the national legislative requirements only, which might be considered constraints rather than targets. Identifying appropriate targets for these fisheries should be defined by the management authority.

Stakeholders were invited to provide information to the review meeting. Representative fishermen from the US Caribbean were present at the meeting. This was very helpful and they provided important background information on the fishery and the socio-economics that could explain past observations. However, they expressed their concerns with socio-economic issues, which was not within the Review Panel's scope. While this was not a problem for the review, it did suggest to me that the fishermen may not fully understand the SEDAR process, which may limit their ability to be fully involved and to ensure their concerns are addressed. This would not help co-operation with the fisheries management or, for example, with data collection initiatives.

The main concern over the SEDAR ToRs was the way they were written inherits language from data rich assessments. Decision analysis focuses on risk associated with actions rather than estimating the current state of the system being assessed. It may be useful to reword ToRs to address risk, couched in terms more consistent with the performance indicators being used.

7.4 Other Recommendations

It is not possible to manage fisheries effectively unless monitoring data are collected. Any data limited method should encourage data collection, so stakeholders can clearly perceive the advantage with providing good monitoring data. The overarching aim should be to collect more and better information which should lead to lower risk and higher long term yields.

As a result, desirable qualities of a decision analysis include:

- a smooth transition as data are incorporated from prior estimates to more accurate estimates which are determined primarily by the data likelihood. For this to work, the log-likelihood and log-priors need to be suitably balanced. Inappropriate weighting could lead to dramatic changes in the assessment as data are added which would be undesirable.
- A reduction in uncertainty as data are added, so that risks are reduced from observations.

Using the DLMtool alone, because it does not use any data directly, does not address the issue. However, allowing DLMtool to accept parameter random draws from other models would allow, for example, the use of MCMC or bootstrap outputs where information exists. This would resolve a number of issues with the DLMtool projections.

I would strongly recommend that the analytical team explore a formal Bayesian approach to the assessment of some of these stocks, to see whether the projections used for the MSE can be better conditioned on the available data. Currently, the projections rely on uninformative priors on many parameters, so simulations cover a very wide range of possible outcomes. Reducing this range of possible outcomes will likely lead to improved assessments for the MPs, and ultimately could lead to formal stock assessments in some cases. Appendix 4 contains an illustration of the type of model which might be fitted with recent software (e.g. mc-stan.org). This recommendation is made with the caveat that the software may not work in all circumstances, dependent on the available data.

Among other things, the Bayesian method provides a natural transition from no data, through data limited to data rich assessments. The data should provide information progressively, so that the results become increasingly accurate as data are collected. This in turn should lead to clear positive feedback for the management and fishing industry as catches and catch rates should become more stable and increase with improved decision-making. The example in Appendix 4 illustrates how adding more information reduces uncertainty because the probable stock dynamics are reduced to those that remain consistent with the past data.

8 ToR 5: Consider whether the stock assessment constitutes the best scientific information available using the following criteria as appropriate: relevance, inclusiveness, objectivity, transparency, timeliness, verification, validation, and peer review of fishery management information.

The review covered the application of decision analysis on possible MPs setting catch limits for six stocks. These were trial runs of the testing procedure, but some MPs were identified as appropriate. I would recommend using these potential MPs for setting catch limits. This is based on the sufficiency and quality of the data, the model assumptions, and performance metrics from the MSE using the reviewer revisions and the biased/imprecise input data. The results have been provided in the main DW/AW report and the Reviewer Workshop addendum from the analytical team. Notwithstanding further work on improving these, the proposed MPs clearly outperform current MPs.

The analytical team, through the DW and AW, have carried out a careful assessment making good use of the available information. The assessment used most of the available information to identify good management procedures for setting quotas for the fisheries examined. The assessment of the procedure was for the ABC rather than the ACL as it explicitly takes risk into account. In this sense, the assessment used the best scientific information.

Some improvements are possible, and the method is a work in progress. Further diagnostics for the DLMtool projections would demonstrate more clearly that the MPs were being tested correctly. Producing diagnostics would be particularly important for any selected MP. Diagnostics would identify incorrect runs or unrealistic behaviour (e.g. reporting whether the max F boundary is hit, the ranges in F, F/FMSY, B, and B/BMSY, time series fluctuations in any indicator).

Some information was not used directly. Not using some data could be justified because the data were not reliable. Nevertheless, the MSE could be conditioned better on the available observations.

All stock assessments include a degree of subjectivity, particularly in the model structure. Objectivity is primarily brought in through the observations. DLMtool does not use data directly, and therefore the MSE is somewhat subjective. DLMtool has been peer reviewed and appears to follow a standard form used in fisheries science. The information used in the DLMtool model has been through a DW review. This is as close to objective as you can get with this approach.

Projections need to be more constrained to reflect possible scenarios. For example, catches for some scenarios were much higher than any observed and would not seem credible. Currently, the way the parameters are randomly selected might overestimate biomass, which may make less risk averse MPs apparently perform better. This has mostly been dealt with by removing MPs for which data are not available. Nevertheless, it would be better for the MSE to match real world for these fisheries as closely as possible, so that they discriminate accurately among MPs for each fishery. This is an important reason why conditioning parameter inputs is desirable.

Presentation of the information and results was very good. This is a complex assessment, and summary information is critical for managers and stakeholders to understand.

A number of MPs were included in the test which seemed inappropriate to these fisheries. For example, the MPs requiring absolute abundance estimates are probably only relevant where good abundance estimates are available (e.g. biomass surveys). It would be better to either exclude them from testing based on an initial qualitative assessment, or include performance indicators that identified their weakness in the tests themselves.

9 ToR 6: Provide guidance on key improvements in data or modeling approaches that should be considered when scheduling the next assessment.

Although the methods are robust to a lack of data, it is still recommended data are improved where possible. A lack of data will result in harvest levels that primarily avoid over-exploitation, while also reduce opportunities to harvest resources. Furthermore, precise data, such as total catches and length sampling, are still required to implement the management procedures.

It is important that known strong correlations between parameters, notably L_∞ and K, and the length-weight parameters a and b (if they are not fixed estimates), should be accounted for in the parameter density functions. Joint parameter probability density functions (pdf) would be less variable than currently simulated. More generally, the DLMtool software could be enhanced by allowing random parameters to be provided to the models rather than simple parametric probability density functions.

Selectivity may be an important consideration for some of these fisheries. As suggested by the review panel, setting Lc parameter to the mode of the length frequency makes sense as this would correspond to the point of full selection when assuming knife-edge selectivity. Domed selectivity is likely to apply to the spiny lobster fisheries, at least for diving, and fisheries affected by ciguatera.

Unrealistic scenarios (e.g. very high abundances / catches) should be removed from the projection simulations. This can be achieved by conditioning the operational model on the available data. Joint pdfs (see above) should help with this issue.

Presentation of information was good, particularly the summary information. However, more time series plots (e.g. simulation density for key indicators) and indicators such as F/FMSY and B/MSY should be reported. Diagnostics for the MSE should be routinely reported so that it can be seen that they have run correctly.

Performance indicators for the MPs should cover all requirements on MPs, so that MPs can be rejected based on performance criteria rather than for other external reasons. The measures of short term yield and yields relative to the current yields might be useful in this respect. MP assessment would also be improved with identified targets, although some guidance from managers on management objectives would be useful for this.

Simulated data for the management procedures should reflect the properties of real data (i.e. be imprecise and biased). The MSE should assume the available data is biased and imprecise as the default. In data limited fisheries, management procedures should be selected on the basis that they are robust to poor data as well as limited data, as these almost always occur together. In addition, MPs which require information that is not available should be excluded from testing (an “MP triage”), as including them gives misleading results. This should also make the assessment of MPs more efficient.

The most efficient method to obtain a sufficiently precise estimate of the performance indicators should be used. The current number of projections may be excessive and make the assessments time consuming. The projection length and number of simulations should be tested to ensure they are as efficient as possible but sufficient for their use. This could be achieved by a statistical test for convergence at the start of simulations rather than relying on graphical output. Unless there is a need to contrast repeats (a random draw of recruitments) with simulations (a random draw of all parameters), only simulations may be required, which again could increase the analysis efficiency.

10 ToR 7: CIE Reviewers may contribute to a Peer Review Summary summarizing the Panel’s evaluation of the stock assessment and addressing each Term of Reference.

A separate Review Panel summary report was produced.

11 References

Berger, J.O. 1993. Statistical Decision Theory and Bayesian Analysis. 2nd Edition. Springer Series in Statistics. Springer, New York.

Peterman, R.M., Peters, C.N., Robb, C.A., Frederick, S.W. 1998. Bayesian decision analysis and uncertainty in fisheries management. In: Pitcher, T.J., Hart, P., Pauly, D. (Eds.) Reinventing Fisheries Management. Fish & Fisheries Series Volume 23: pp 387-398. Springer, New York.

Punt, A.E., Hilborn, R. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries 7(1): 35-63.

STAN 2015. Stan Development Team 2015. Stan Modeling Language: User’s Guide and Reference Manual. Version 2.9.0.

12 Appendix 1: Bibliography of materials provided for review

Documents Prepared for the Review Workshop			
SEDAR46-RW-01	Estimating total mortality rates and calculating overfishing limits from length observations for six U.S. Caribbean stocks	Quang C. Huynh	14 Jan 2016
SEDAR46-RW-02	Management strategy evaluations for mean length-based management procedures using DLMtool	Quang C. Huynh	22 Feb 2016
SEDAR46-RW-03	An alternative approach to setting annual catch limits for data-limited fisheries: Use of the DLMtool and mean length estimator for six US Caribbean stocks	Nancie Cummings, Skyler Sagarese and Quang C. Huynh	22 Feb 2016

Reference Documents Submitted during the Review Workshop		
SEDAR46-RD04	Evaluating methods for setting catch limits in data-limited fisheries	Thomas R. Carruthers, André E. Punt, Carl J. Walters, Alec MacCall, Murdoch K. McAllister, Edward J. Dick, Jason Cope
SEDAR46-RD05	Evaluating methods for setting catch limits in data-limited fisheries: Supplemental Appendix A	Thomas R. Carruthers, André E. Punt, Carl J. Walters, Alec MacCall, Murdoch K. McAllister, Edward J. Dick, Jason Cope
SEDAR46-RD06	DLMtool: Data-Limited Methods Toolkit (v2.1.1)	Tom Carruthers and Adrian Hordyk
SEDAR46-RD07	Length-based assessment of sustainability benchmarks for coral reef fishes in Puerto Rico	Jerald S. Ault, Steven G. Smith, Jiangang Luo, Mark E. Monaco, and Richard S. Appeldoorn
SEDAR46-RD08	Data Limited Techniques for Tier 4 Stocks: An alternative approach to setting harvest control rules using closed loop simulations for management strategy evaluation	Jason McNamee, Gavin Fay, and Steven Cadrin
SEDAR46-RD09	Application of Data-Poor Harvest Control Rules to Atlantic Mackerel	John Wiedenmann
SEDAR46-RD10	September 2015 Mid-Atlantic SSC Meeting Report – Black Sea Bass Review	Mid-Atlantic SSC
SEDAR46-RD11	Stock assessment of protogynous fish: evaluating measures of spawning biomass used to estimate biological reference points	Elizabeth N. Brooks, Kyle W. Shertzer, Todd Gedamke, and Douglas S. Vaughan

13 Appendix 2: A copy of the CIE Statement of Work

Statement of Work

External Independent Peer Review by the Center for Independent Experts

SEDAR 46 US Caribbean Data Limited Species Assessment Review Workshop

Scope of Work and CIE Process: The National Marine Fisheries Service's (NMFS) Office of Science and Technology coordinates and manages a contract providing external expertise through the Center for Independent Experts (CIE) to conduct independent peer reviews of NMFS scientific projects. The Statement of Work (SoW) described herein was established by the NMFS Project Contact and Contracting Officer's Technical Representative (COTR), and reviewed by CIE for compliance with their policy for providing independent expertise that can provide impartial and independent peer review without conflicts of interest. CIE reviewers are selected by the CIE Steering Committee and CIE Coordination Team to conduct the independent peer review of NMFS science in compliance the predetermined Terms of Reference (ToRs) of the peer review. Each CIE reviewer is contracted to deliver an independent peer review report to be approved by the CIE Steering Committee and the report is to be formatted with content requirements as specified in **Annex 1**. This SoW describes the work tasks and deliverables of the CIE reviewer for conducting an independent peer review of the following NMFS project. Further information on the CIE process can be obtained from www.ciereviews.org.

Project Description: SEDAR 46 will be a compilation of data, an assessment of the stocks, and CIE assessment review conducted for Caribbean Data-limited Species. The review workshop provides an independent peer review of SEDAR stock assessments. The term review is applied broadly, as the review panel may request additional analyses, error corrections and sensitivity runs of the assessment models provided by the assessment panel. The review panel is ultimately responsible for ensuring that the best possible assessment is provided through the SEDAR process. The stocks assessed through SEDAR 46 are within the jurisdiction of the Caribbean Fisheries Management Council and the territorial waters of Puerto Rico and the U.S. Virgin Islands. The Terms of Reference (ToRs) of the peer review are attached in **Annex 2**. The tentative agenda of the panel review meeting is attached in **Annex 3**.

Requirements for CIE Reviewers: Three CIE reviewers shall conduct an impartial and independent peer review in accordance with the SoW and ToRs herein. CIE reviewers shall have working knowledge expertise in stock assessment, statistics, fisheries science, and marine biology sufficient to complete the primary task of providing peer-review advice in compliance with the workshop Terms of Reference. Experience with data-limited assessment methods would be preferred. Each CIE reviewer's duties shall not exceed a maximum of 14 days to complete all work tasks of the peer review described herein.

Location of Peer Review: Each CIE reviewer shall conduct an independent peer review during the panel review meeting scheduled in **Miami, Florida during February 23-25, 2016**.

Statement of Tasks: Each CIE reviewers shall complete the following tasks in accordance with the SoW and Schedule of Milestones and Deliverables herein.

Prior to the Peer Review: Upon completion of the CIE reviewer selection by the CIE Steering

Committee, the CIE shall provide the CIE reviewer information (full name, title, affiliation, country, address, email) to the COTR, who forwards this information to the NMFS Project Contact no later the date specified in the Schedule of Milestones and Deliverables. The CIE is responsible for providing the SoW and ToRs to the CIE reviewers. The NMFS Project Contact is responsible for providing the CIE reviewers with the background documents, reports, foreign national security clearance, and other information concerning pertinent meeting arrangements. The NMFS Project Contact is also responsible for providing the Chair a copy of the SoW in advance of the panel review meeting. Any changes to the SoW or ToRs must be made through the COTR prior to the commencement of the peer review.

Foreign National Security Clearance: When CIE reviewers participate during a panel review meeting at a government facility, the NMFS Project Contact is responsible for obtaining the Foreign National Security Clearance approval for CIE reviewers who are non-US citizens. For this reason, the CIE 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 NMFS Project Contact for the purpose of their security clearance, and this information shall be submitted at least 30 days before the peer review in accordance with the NOAA Deemed Export Technology Control Program NAO 207-12 regulations available at the Deemed Exports NAO website: http://deemedexports.noaa.gov/ http://deemedexports.noaa.gov/compliance_access_control_procedures/noaa-foreign-national-registration-system.html

Pre-review Background Documents: Two weeks before the peer review, the NMFS 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 NMFS Project Contact will consult with the CIE Lead Coordinator on where to send documents. CIE reviewers are responsible only for the pre-review documents that are delivered to the reviewer in accordance to the SoW scheduled deadlines specified herein. The CIE reviewers shall read all documents in preparation for the peer review.

Panel Review Meeting: Each CIE reviewer shall conduct the independent peer review in accordance with the SoW and ToRs, and shall not serve in any other role unless specified herein. **Modifications to the SoW and ToRs cannot be made during the peer review, and any SoW or ToRs modifications prior to the peer review shall be approved by the COTR and CIE Lead Coordinator.** Each CIE reviewer shall actively participate in a professional and respectful manner as a member of the meeting review panel, and their peer review tasks shall be focused on the ToRs as specified herein. The NMFS Project Contact is responsible for any facility arrangements (e.g., conference room for panel review meetings or teleconference arrangements). The NMFS Project Contact is responsible for ensuring that the Chair understands the contractual role of the CIE reviewers as specified herein. The CIE Lead Coordinator can contact the Project Contact to confirm any peer review arrangements, including the meeting facility arrangements.

CIE reviewers shall conduct an impartial and independent peer review of the assessment in accordance with the SoW and ToRs herein.

A description of the SEDAR Review process can be found in the SEDAR Policies and Procedures document:
http://sedarweb.org/docs/page/A6-SEDARPoliciesandProcedures_June2014_0.pdf

The CIE reviewers may contribute to a Summary Report of the Review Workshop produced by the Workshop Panel.

Contract Deliverables - Independent CIE Peer Review Reports: Each CIE reviewer shall complete an independent peer review report in accordance with the SoW. Each CIE reviewer shall complete the independent peer review according to required format and content as described in Annex 1. Each CIE reviewer shall complete the independent peer review addressing each ToR as described in Annex 2.

Other Tasks – Contribution to Summary Report: Each CIE reviewer may assist the Chair of the panel review meeting with contributions to the Summary Report, based on the terms of reference of the review. Each CIE reviewer is not required to reach a consensus, and should provide a brief summary of the reviewer's views on the summary of findings and conclusions reached by the review panel in accordance with the ToRs.

Specific Tasks for CIE Reviewers: The following chronological list of tasks shall be completed by each CIE reviewer in a timely manner as specified in the **Schedule of Milestones and Deliverables**.

1) Conduct necessary pre-review preparations, including the review of background material and reports provided by the NMFS Project Contact in advance of the peer review.
2) Participate during panel review meeting in **Miami, FL during February 23-25, 2016,** as specified herein, and conduct an independent peer review in accordance with the ToRs (**Annex 2**).
3) No later than March 10, 2016, each CIE reviewer shall submit an independent peer review report addressed to the "Center for Independent Experts," and sent to Dr. Manoj Shivlani, CIE Lead Coordinator, via email to mshivlani@ntvifederal.net, and Dr. David Sampson, CIE Regional Coordinator, via email to david.sampson@oregonstate.edu. Each CIE report shall be written using the format and content requirements specified in Annex 1, and address each ToR in **Annex 2**.

Schedule of Milestones and Deliverables: CIE shall complete the tasks and deliverables described in this SoW in accordance with the following schedule.

January 12, 2016	CIE sends reviewer contact information to the COTR, who then sends this to the NMFS Project Contact
February 9, 2016	NMFS Project Contact sends the CIE Reviewers the pre-review documents
February 23-25, 2016	Each reviewer participates and conducts an independent peer review during the panel review meeting
March 10, 2016	CIE reviewers submit draft CIE independent peer review reports to the CIE Lead Coordinator and CIE Regional Coordinator
March 24, 2016	CIE submits CIE independent peer review reports to the COTR
March 31, 2016	The COTR distributes the final CIE reports to the NMFS Project Contact and regional Center Director

Modifications to the Statement of Work: This 'Time and Materials' task order may require an update or modification due to possible changes to the terms of reference or schedule of milestones resulting from the fishery management decision process of the NOAA Leadership, Fishery Management Council, and Council's SSC advisory committee. A request to modify this SoW must be approved by the Contracting Officer at least 15 working days prior to making any permanent changes. The Contracting Officer will notify the COTR within 10 working days after receipt of all required information of the decision on changes. The COTR can approve changes to the milestone dates, list of pre-review documents, and ToRs within the SoW as long as the role and ability of the CIE reviewers to complete the deliverable in accordance with the SoW is not adversely impacted. The SoW and ToRs shall not be changed once the peer review has begun.

Acceptance of Deliverables: Upon review and acceptance of the CIE independent peer review reports by the CIE Lead Coordinator, Regional Coordinator, and Steering Committee, these reports shall be sent to the COTR for final approval as contract deliverables based on compliance with the SoW and ToRs. As specified in the Schedule of Milestones and Deliverables, the CIE shall send via e-mail the contract deliverables (CIE independent peer review reports) to the COTR (Allen Shimada, allen.shimada@noaa.gov).

Applicable Performance Standards: The contract is successfully completed when the COTR provides final approval of the contract deliverables. The acceptance of the contract deliverables shall be based on three performance standards:
(1) The CIE report shall be completed with the format and content in accordance with **Annex 1**,
(2) The CIE report shall address each ToR as specified in **Annex 2**,
(3) The CIE reports shall be delivered in a timely manner as specified in the schedule of milestones and deliverables.

Distribution of Approved Deliverables: Upon acceptance by the COTR, the CIE Lead Coordinator shall send via e-mail the final CIE reports in *.PDF format to the COTR. The COTR will distribute the CIE reports to the NMFS Project Contact and Center Director.

Support Personnel:

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Annex 1: Format and Contents of CIE Independent Peer Review Report

1. The CIE independent report shall be prefaced with an Executive Summary providing a concise summary of the findings and recommendations, and specify whether the science reviewed is the best scientific information available.

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

d. Reviewers shall provide a critique of the NMFS review process, including suggestions for improvements of both process and products.

e. 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 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 Statement of Work
Appendix 3: Panel Membership or other pertinent information from the panel review meeting.

Annex 2: Terms of Reference for the Peer Review

SEDAR 46 US Caribbean Data Limited Species Assessment Review Workshop

1. Evaluation, findings and recommendations of data collection operations and survey design
2. Evaluation and recommendations of data quality
3. Evaluation of strengths and weaknesses, and recommendations of analytic methodologies
4. Evaluation and recommendations of model assumptions, estimates, and uncertainty
5. Evaluation, findings, and recommendations of result interpretation and conclusions
6. Determine whether the the science reviewed is considered to be the best scientific information available.
7. Recommendations for further improvements
8. Brief description on panel review proceedings highlighting pertinent discussions, issues, effectiveness, and recommendations

Annex 3: Tentative Agenda
SEDAR 46 US Caribbean Data Limited Species Assessment Review Workshop

Miami, Florida
February 23-25, 2016

Tuesday
9:00 a.m. Introductions and Opening Remarks Coordinator
- *Agenda Review, TOR, Task Assignments*

9:30 a.m. – 11:30 a.m. Assessment Presentations Analytic Team
- *Assessment Data & Methods*
- *Identify additional analyses, sensitivities, corrections*

11:30 a.m. – 1:00 p.m. Lunch Break
1:00 p.m. – 6:00 p.m. Assessment Presentations (continued) Analytic Team
- *Assessment Data & Methods*
- *Identify additional analyses, sensitivities, corrections*

6:00 p.m. – 6:30 p.m. Public comment Chair
Tuesday Goals**:** Initial presentations completed, sensitivity and base model discussion begun

Wednesday
8:00 a.m. – 11:30 a.m. Panel Discussion Chair
- *Assessment Data & Methods*
- *Identify additional analyses, sensitivities, corrections*

11:30 a.m. – 1:00 p.m. Lunch Break
1:00 p.m. – 6:00 p.m. Panel Discussion/Panel Work Session Chair
- *Continue deliberations*
- *Review additional analyses*
- *Recommendations and comments*

6:00 p.m. – 6:30 p.m. Public comment Chair
Wednesday Goals**:** sensitivities and modifications identified, preferred models selected, projection approaches approved, Report drafts begun

Thursday
8:00 a.m. – 11:30 a.m. Panel Discussion Chair
- *Final sensitivities reviewed.*
- *Projections reviewed.* **Chair**

11:30 a.m. – 1:00 p.m. Lunch Break
1:00 p.m. – 5:30 p.m. Panel Discussion or Work Session Chair
- *Review Reports*

5:30 p.m. – 6:00 p.m. Public comment Chair
6:00 p.m. ADJOURN

Thursday Goals: Complete assessment work and discussions, final results available. Draft Reports reviewed.

14 Appendix 3: Review Workshop Panel Membership

Vance P. Vicinte, Chair .... Chair, SSC
Panayiota Apostolaki .... CIE Reviewer
Jerald S. Ault ....Council Appointee
Cathy Dichmont .... CIE Reviewer
John Hoenig .... SSC
Paul Medley .... CIE Reviewer

15 Appendix 4: Bayesian Operational Model

15.1 Introduction

To test the idea of partially fitting the operational model used in DLM tools to the available data, I used a standard age structured model (i.e. close to that used for the DLM tools projections) fitted to the available St Croix spiny lobster data (total catch, abundance index and length compositions from the SEDAR 46 DW/AW Final Report Appendix 4.3.5 Page 261 "SpinyLobster_STX-dive"). The fit illustrates the issues in fitting this sort of operational model where data are limited.

Realistic operational models are over-parameterised in data limited situations, so it is not possible to use maximum likelihood to fit them. The only way is to use informative priors together with the likelihood using Bayes rule. Given the operational model used for the DLMtools is based on priors, it remains to be tested whether any data can be incorporated to useful effect.

For this illustration, the operational model is simpler than what the DLM tool uses (stock-recruitment, selectivity and various gradients and variances are not fitted). This model primarily fits some important stock model parameters and fishing mortality. Other parameters required by the DLMtool operating model will still need to be set as previously.

The theory behind fitting complex models to limited data, such as random effects or latent variables and Bayes rule, have been well understood for many years. The practical fitting of such models has been the main limiting factor. While I do not believe this is a trouble-free process, new software is being developed which appears to have increased the possibilities of this approach.

Bayesian statistics provides a comprehensive framework to develop decision analysis. The DLMtool approach described essentially uses a Bayesian assessment based on priors only, although many of the priors incorporate empirical information so are effectively informal posteriors. A utility function based on US Fisheries Management requirements is used to score various management procedures. An important component of Bayesian decision analysis is to incorporate observations through a likelihood function. This is missing from the current approach.

I use a similar approach for the data limited fisheries that I work on, but with a few important differences. The greatest difference is I still try to fit simpler models to any available data alongside informative priors. Where it is not possible to estimate stock status with any confidence, it may still be possible to proscribe a harvest control rule (management procedure) which can reliably sustain the fishery. The other major differences are in the rules I test, which are not constrained by US fisheries management requirements (for example, I usually do not recommend catch limits), although these management procedures still broadly have the same objectives.

In theory, the model starts with priors on parameters, which are then adjusted based on observations using Bayes rule. Where an observation contains information on a parameter, its probability will be affected. If an observation has no information, the prior would continue to apply. For example, if we added length and weight data to the assessment model, the *a* and *b* parameters for the length-weight relationship would be updated, other parameters would remain untouched. In practice, these non-linear models are more difficult to manage, so adding data may introduce distortions that can cause unrealistic changes in parameter estimates.

Fitting these highly parameterised models is problematic. It requires methods to carry out efficient Monte Carlo integration so that nuisance parameters and random effects can be integrated to obtain marginal probability density functions of interest. Previous algorithms to do this that work with large numbers of parameters, MCMC Metropolis-Hastings samplers, usually do not work for these models. This is primarily because parameters are highly correlated in fisheries time series models, and the Metropolis-Hastings approach performs poorly with highly correlated parameters. Recently alternative software has been released which attempts to provide more efficient MCMC sampling. The example I use here is STAN (mc-stan.org), which has an R interface. This is based on models of particle movement governed by energy levels (Hamiltonian), and includes auto-differentiation in determining directions for random movement over the probability density. Another sampler which I have not tried, but could be promising, is Library for Bayesian Inference (LiBBi.org). The LiBBi algorithms may be more appropriate for state-space models, but there is no R interface yet for this software.

15.2 Method and Results

An age structure model similar to the DLMtool model was fitted to the available St Croix spiny lobster dive data (total catch, abundance index and length compositions from the SEDAR 46 DW/AW Final Report Appendix 4.3.5 Page 261 "SpinyLobster_STX-dive"). The choice of fishery was arbitrary, except I am most familiar with spiny lobster life history. The STAN code used to fit the model is in Annex A.

The MCMC was conducted on three versions of the model. Firstly, the sampler was applied to the prior only. These are approximately the same probabilities used for the DLM tool projections, so the results should be broadly comparable. In some cases, the priors were more constrained to ensure consistent fitting (e.g. natural mortality was limited to lie between 0.3 and 0.4 year^{-1}). Clearly, it is inefficient to use MCMC when draws can be made from the independent probability density functions directly, but was useful for this illustration. The second model was exactly the same, but included the likelihood for the catch and abundance index data. This gives information on abundance, but no direct information on size or growth. The third model was again the same, but as well as being fitted to the total catch and abundance index data, included the size composition data, which represented all the information available.

Four MCMC chains were run in parallel, and these chains were compared to test for convergence. STAN provides a number of diagnostic checks. Importantly, the convergence statistic, $\hat{R}$, indicated convergence for all parameters across all four chains (STAN 2015). However, as this was an illustration only, start points for the chains, which can affect convergence, were not exhaustively examined.

It is important to note that this is a formal statistical fit of the operational model to the data. It will be heavily influenced by the priors, so it will not be entirely objective. However, at worst, it provides a set of random parameters for the DLMtool projections that have been conditioned on the available observations, so unrealistic parameter combinations are excluded, and the frequency of parameters in the random set reflects the probability of them being true. At best, the fit provides the same output as might be expected from a data-rich stock assessment, albeit the uncertainty in results might be expected to be large, reflected in wide confidence intervals in results.

The growth parameters are represented by L_∞, K and Ls (the standard deviation for the length-at-age). t_0 and age at recruitment were fixed. Differences between these parameter probabilities were low between the prior and posterior using only the catch and abundance index (Figure 1). However, the estimate for K shifted to a lower level even though there is no direct information on growth rate from the catch and abundance index data. These models will adjust parameters with least resistance to explain observations regardless of whether this makes sense. This can be avoided by constraining parameters (e.g. fixing them when fitting the likelihood, but using priors for the projections) or models (i.e. fitting sub-models separately to create posteriors for input to the main model) or, more properly, defining the priors more accurately on the right scale, in balance with the likelihood. Where a range of data are available that contain information on all parameters, this is less of a problem.

Including the size composition data, not surprisingly, does influence growth parameters, shifting the estimates and reducing the variance (Figure 1, Table 1). Importantly, the L_∞ and K parameters become highly correlated (Figure 1), a feature the review panel noted was absent from the DLMtool projections.

Using data has a dramatic effect on estimation of biomass. Using priors only, biomass is not well defined, but adding past catches and abundance indices greatly increases the precision of the estimates (Figure 2). Using the priors only for projections would result in a very widely varying biomass, so management procedures that account for different abundance would likely be favoured even though some biomass levels are wildly optimistic. This may suggest using unconditioned parameter probability functions, particularly using log-normal probability, could bias MPs based on catch limits towards performing better in simulations than they can in reality.

Note that informative priors of fishing mortality were used (beta(2,8)), which may have biased the biomass estimates through the early part of the time series when the recorded catches were low. The size composition data does not indicate that fishing mortality was particularly low during this period. For a full assessment, unknown parameters would more likely be modelled as uniform on some reasonable range, although this could lead to difficulties in achieving MCMC convergence.

The early part of the time series could be excluded if the catch data were considered unreliable to 2000, when the abundance index starts. Alternatively, additional parameters could be used to account for unrecorded catch. While theoretically this is possible, it can result in considerable work creating nuisance parameters which reduce the information from the data on parameters of interest to a negligible level. Nuisance parameters with informative priors estimating the recorded catch as a proportion of the true total catch would still allow the other data (length compositions) to be used. Whether it would be worth including or excluding these data would need to be explored.

Another potential problem with this model is the knife-edged selectivity function. For a dive-based spiny lobster fishery, selectivity may well be domed. Without accounting for this, growth parameters may well be biased. Although the estimated L_∞ was in the low-high range (155-210mm), the estimates of K when including the data generally lay outside the low-high range (0.20-0.28) considered in sensitivity analyses. Note that the prior could be used to constrain this parameter within the range.

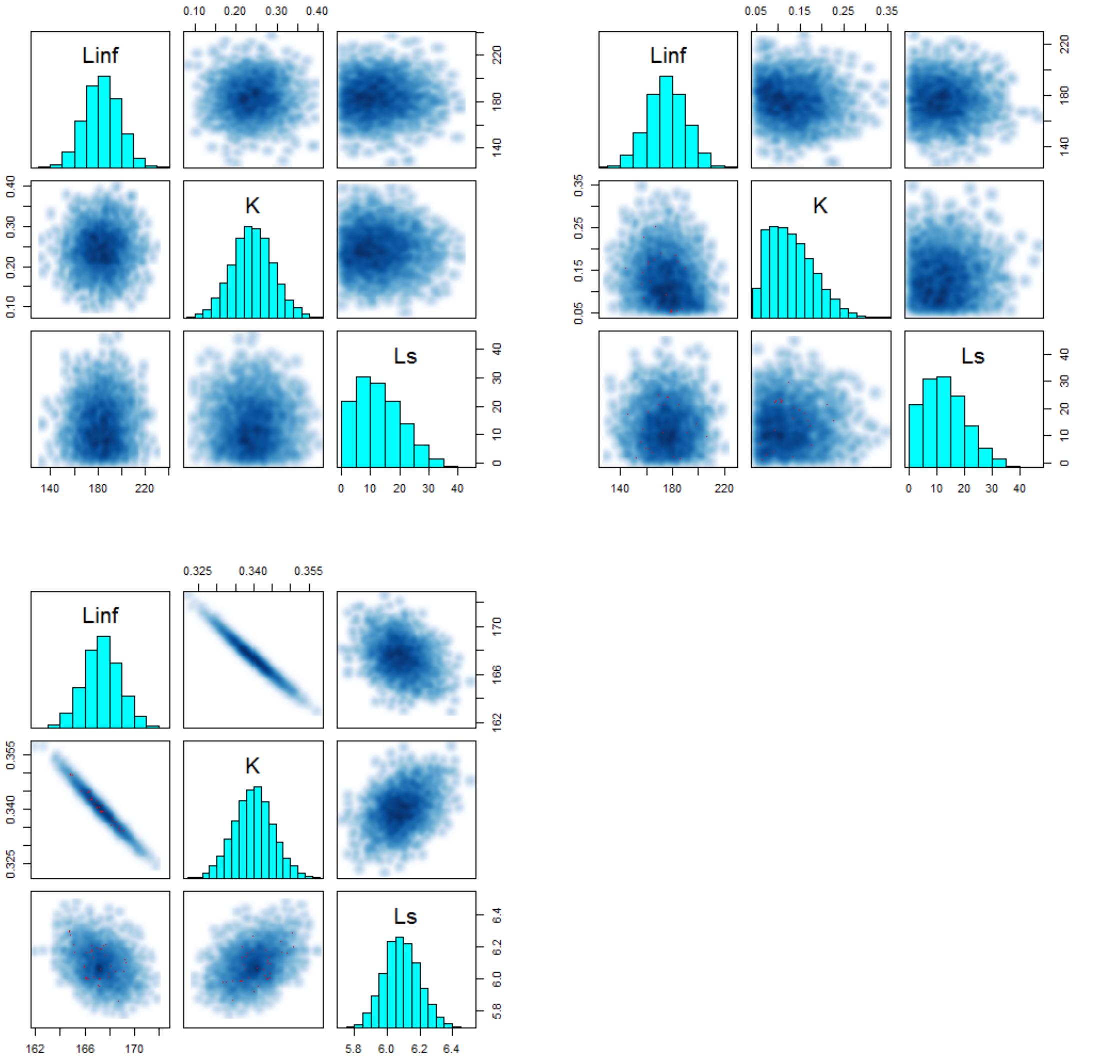

Figure 1 “Pairs” plot for 3 growth parameters for the prior (top left), posterior based on total catch and the abundance index (top right), and posterior based on total catch, abundance index and length compositions (bottom left). Linf and K are von Bertalanffy growth model and Ls is the standard deviation for the length-at-age. Red dots for the posterior plots indicate divergent steps in the MCMC algorithm, suggesting that further work is required to complete the model fit.

Table 1 Mean and standard deviation of the MCMC draws for selected hyper-parameters for the operational model. The model fitted 105 parameters in all, 93 of which are "random effects".

	Prior		Catch / Abundance Index Data		All Data	
	Mean	sd	Mean	sd	Mean	sd
Mean Log-recruitment	7.01	1.43	5.39	0.35	5.21	0.19
Standard deviation Log-recruitment	1.00	0.20	1.44	0.14	1.38	0.12
Log-catchability	-17.95	1.95	-13.73	0.20	-13.17	0.13
Natural Mortality	0.35	0.01	0.35	0.01	0.38	0.01
Linf	183.26	14.70	175.60	14.70	167.36	1.44
K	0.24	0.05	0.13	0.05	0.34	0.01
Ls	13.06	8.04	13.05	7.77	6.09	0.11

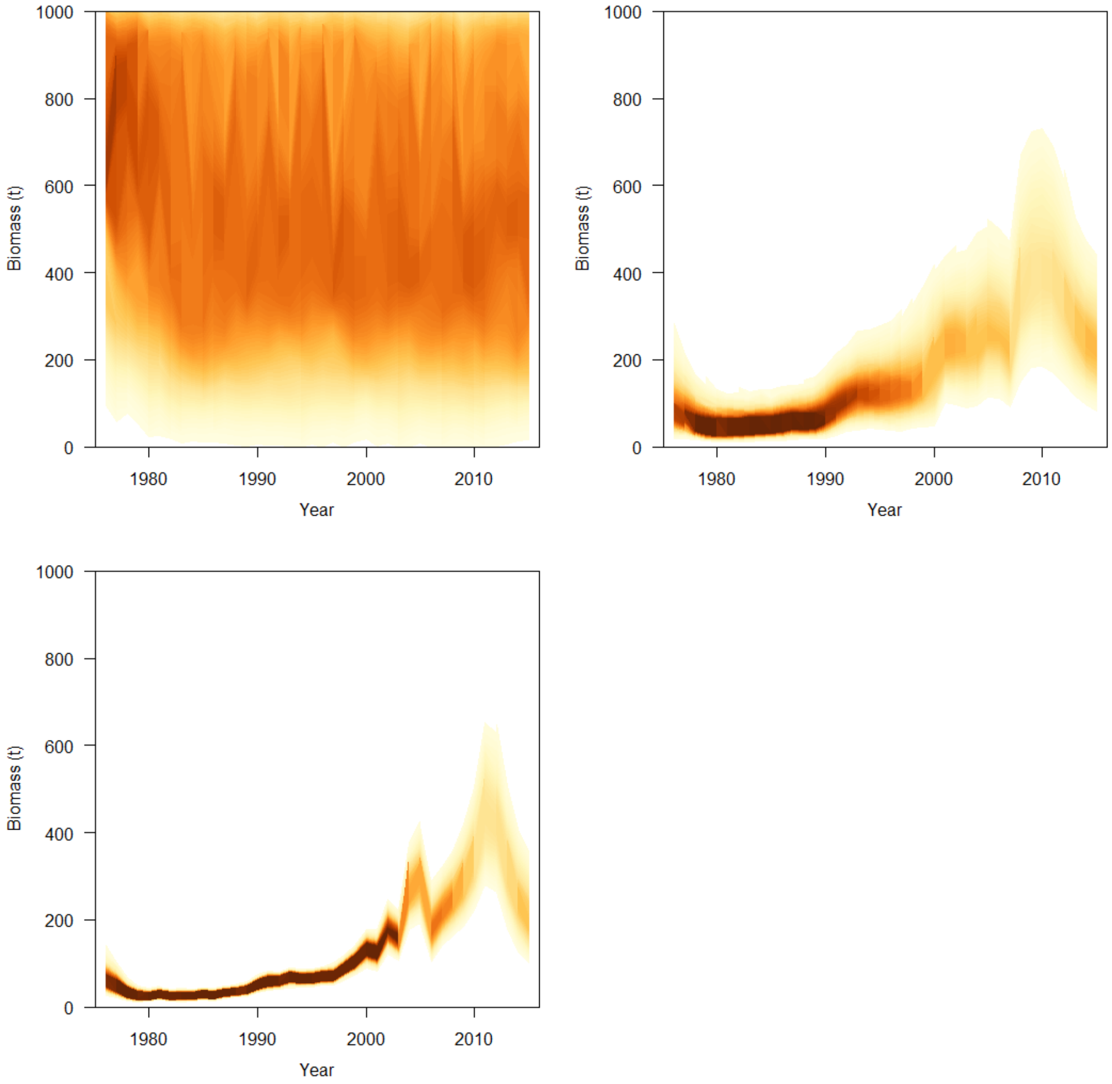

Figure 2 Watercolour plots of probability densities for the Puerto Rico spiny lobster biomass based on the prior (top left), the posterior using only the total catch and the abundance index data (top right), and the posterior including the size composition data with the catch and abundance index (bottom left).

15.3 References

STAN 2015. Stan Development Team 2015. *Stan Modeling Language: User's Guide* and Reference Manual. Version 2.9.0.