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Title: Identification and prioritization of uncertainties for management of Eastern Atlantic Bluefin Tuna (Thunnus thynnus)

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Abstract: In recent decades there has been steady progress towards a risk-based management approach for fisheries. An important first step in a risk analysis framework is scoping to identify, describe and catalogue the sources of uncertainty that might have an impact on a fishery. This paper introduces a methodology based on a novel range of tools to formalize the process of elicitation of uncertainties, from both experts and stakeholders, for the International Commission for the Conservation of Atlantic Tunas (ICCAT). ICCAT is a regional fisheries management organization responsible for the conservation of tunas and other highly migratory fish in the Atlantic Ocean and its adjacent seas. The aim of the elicitation was to identify and prioritize uncertainties for inclusion in Operating Models for Management Strategy Evaluation (MSE). The tool presented in this paper supports the qualitative prioritization of uncertainties, while also visualizing the degree of consensus among stakeholders on particular issues. Perceptions of uncertainty in fisheries often vary widely among scientists, industry and other interest groups, so tools that can facilitate inclusion and representation of different opinions are useful where decision-making depends on broad agreement and more generally, where effective management depends on commitment from stakeholders.

The Steading
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21/02/2014

Dear Hance,

Please find our manuscript entitled "Identification and prioritization of uncertainties for management of Eastern Atlantic Bluefin Tuna (Thunnus thynnus)" resubmitted through the on-line system in which we have responded to each of the queries and corrections of the two reviewers (see below). We hope that the paper is now acceptable for publication in Marine Policy.

If you have any queries suggestions, please do not hesitate to contact me.

Yours sincerely

Adrian Leach pp. Polina Levontin, Johnson Holt, Laurence Kell and John Mumford

***Detailed Response to Reviewers**

REVIEWER 1.

Many thanks to the reviewer for his/her helpful and enjoyable comments.

In response to the second paragraph of the reviewer's opening comments, the reviewer observed that many of the respondents rated the list of factors as moderately (or more) important, uncertain and unrepresented. The factors included in the elicitation were already perceived as being either important, uncertain and/or poorly represented because of their presence in the literature or because they were raised in open forum discussions. The interest for us came from finding out where each of these factors sat in the three dimensions and how much/little consensus there was about each.

1) With regard to the relativism and the Delphi method

The following paragraph has been added to the Discussion (after the line "characterizing perceptions of uncertainties by graphical methods.") to clarify this:

"In the analysis, no weighting was given to the views of individuals based on their experience nor were they challenged on their responses as they would be for example in the Delphi Method [31]. A reason for this was because in this study we were primarily concerned in understanding the current viewpoints of stakeholder prior to conducting MSE. This was to help ensure that the MSE considered the legitimate concerns of stakeholder and then to observe how these viewpoints changed after conducting quantitative analyses to assess the actual impacts on management objectives. A strength of MSE is that it should add stability to the management decision process as management objectives (and how to evaluate how well alternative management procedures meet them given uncertainty) are agreed through a dialogue between scientists, managers and stakeholders [32, 33, 16]. Recording how stakeholders' views change after conducting an MSE will therefore provide a valuable insight into the management and the MSE process."

The reference numbered [16] is:

[16] Fromentin J-M, Bonhommeau S, Arrizabalaga H, Kell LT. The spectre of uncertainty in management of exploited fish stocks: the illustrative case of Atlantic Bluefin tuna. Marine Policy 2014; 47: 8-14.

The following references were added:

[31] Dalkey N, Helmer O. An experimental application of the Delphi method to the use of experts. Management Science 1963; 9: 458-467

[32] Martin TG, Burgman MA, Fidler F, Kuhnert PM, Low-Choy S, McBride M, Mengersen, K.. Eliciting expert knowledge in conservation science. Conservation Biology 2012; 26: 29-38.

[33] Röckmann C, Ulrich C, Dreyer M, Bell E, Borodzicz E, Haapasaari P, Hauge KH, Howell D, Mantyniemi S, Miller CM, Tserpes G, Pastoors M. The added value of participatory modelling in fisheries management – what has been learnt? Marine Policy 2012; 36: 1072-1085

2) With regard to the query regarding: "Finally, immediate graphical feedback provided the participants with the opportunity to verify or amend their answers accordingly".

The following sentence has been amended and a new sentence added to clarify this:

"The immediate graphical feedback provided by the elicitation tool gave respondents the opportunity to review and/or amend their answers accordingly. The questionnaires were completed individually and there was no opportunity for respondents to be influenced by the responses of others."

3) Ln 107 - After enquiring as to whether uncertainties were confounded, what was done with this information:
The following text has been added to line 109:
"Correlations between sources of uncertainty are to be expected as stock assessment data sets seldom have sufficient information to be able to specify key processes impacting a population, which are also often not independent in nature. For example, in the bluefin assessment based on virtual population analysis, a lack of older fish in the plus group could be caused by older fish being less susceptible to capture or senescence. The consequences of either are quite different. Any indication of confounded uncertainties was noted so that they could be addressed in subsequent analyses."

4) Ln 93 typo fixed

5) Novel.
We agree with the reviewer and have removed all mention of the word novel. Many thanks for helping us to avoid this pitfall.

REVIEWER 2. COPY EDITING REQUIREMENTS

Many thanks to the reviewer concerning copy editing requirements.

Responses in order presented in e-mail from Editor:

1. We have indicated the approximate positions of each of the Figures
2. Capitalisation of “marine” fixed
3. Ref 17. doi removed
4. We could not find the excess capitalisation in Ref 29 but applied that approach to other references and excess capitalisation was fixed in refs. 3, 13, 24, 25
5. Shirley Sam has been contacted and colour printing fees explained. As a consequence we shall be only requiring color printing for Figs. 1, 2 and 5 for the printed version but full color Figures are requested for Figs. 1,2,3,4,5 and 7 in the electronic version.
6. Table 1 (a,b,c) has been renamed as Figure 7 and all references to the figure have updated through the text and graphics files
7. See point 6.

Additional comment to copy reviewer: Please note that, with the exception of Figure 6 (TIF), all Figures are submitted in their native Excel format as prescribed by the Author guidelines for Marine Policy.

*Title Page (WITH Author Details)

Identification and prioritization of uncertainties for management of Eastern Atlantic Bluefin Tuna (*Thunnus thynnus*)

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Highlights

- Tools for applying risk-based approaches to fisheries management
- Identification and prioritization of uncertainty with stakeholders
- Visualization of consensus and disagreement between stakeholders
- Towards identification of hypotheses for use in Management Strategy Evaluation
- Management of Atlantic bluefin tuna

Identification and prioritization of uncertainties for management of Eastern Atlantic Bluefin Tuna (*Thunnus thynnus*)

Abstract

In recent decades there has been steady progress towards a risk-based management approach for fisheries. An important first step in a risk analysis framework is scoping to identify, describe and catalogue the sources of uncertainty that might have an impact on a fishery. This paper introduces a methodology based on a range of tools to formalize the process of elicitation of uncertainties, from both experts and stakeholders, for the International Commission for the Conservation of Atlantic Tunas (ICCAT). ICCAT is a regional fisheries management organization responsible for the conservation of tunas and other highly migratory fish in the Atlantic Ocean and its adjacent seas. The aim of the elicitation was to identify and prioritize uncertainties for inclusion in Operating Models for Management Strategy Evaluation (MSE). The tool presented in this paper supports the qualitative prioritization of uncertainties, while also visualizing the degree of consensus among stakeholders on particular issues. Perceptions of uncertainty in fisheries often vary widely among scientists, industry and other interest groups, so tools that can facilitate inclusion and representation of different opinions are useful where decision-making depends on broad agreement and more generally, where effective management depends on commitment from stakeholders.

Keywords

Stock assessment; Risk analysis; Uncertainty; Expert elicitation; Visualization; Bluefin tuna

1. Introduction

Variability in the natural world and our ability to measure it are not the only sources of uncertainty to affect decisions in managing fisheries; the perceptions and values of scientists, managers, fishers and other stakeholders are also important. However attempts to take such evidence into consideration in day-to-day management processes have been slow [1]. Accounting for uncertainty through risk-based management has been a goal of fisheries management for some time [2], first formalized as 'the precautionary approach' by FAO [3]. In some regions, such as Australia, the precautionary approach evolved into a risk analysis framework, the initial stages of which involve a qualitative assessment of risks through stakeholder elicitations [4].

Risk analysis[1] is a process in which risks are identified (scoped), assessed, managed and communicated [5, 6, 7]. In a fisheries context, Fletcher et al. [8] detail the entire (ecological) risk assessment process while in Fletcher [4] there is a focus on the first two stages consisting of scoping via structured stakeholder elicitations of uncertainties and qualitative assessment of impacts and their likelihood (risk assessment).

Formal elicitation methods have been developed and applied to expert knowledge in fisheries [4] and other fields [9, 10]. These methods may include interviews, workshops, repeatable performance feedback and questionnaires, all designed to ensure that experts give consistent responses [11, 12]. Methods usually emphasize the need to elicit information in such a way that the reasoning behind the judgments are transparent and that these judgments are given on the

[1] The terms risk assessment and risk analysis have been used interchangeably in various standards, so ISO 31000:2009 [7] includes risk analysis as a sub-component of the risk assessment process whereas FAO (2004) [6] refers to risk assessment as being a sub-component within risk analysis. Where risk assessment is applied to the sub-component, the standards are referring to the same process in which there is (semi-)quantification and synthesis of available knowledge upon which management actions can be based. In this paper the term risk analysis is used as the overarching description of a procedure which includes concern (identification), assessment, management and communication.

basis of all relevant information [12]. These principles form the basis of development and application of the methodology presented in this paper; in particular, transparency and feedback were achieved by interactive visualization in the representation of uncertainty. This paper employs an elicitation methodology to scope sources of uncertainty for Eastern Atlantic Bluefin Tuna as the first step of a risk analysis.

The International Commission for the Conservation of Atlantic Tunas (ICCAT) rebuilding plan uses stochastic projections that do not currently capture all the uncertainty associated with stock assessment/management variables [13]. The stock assessment and catch quota outcomes predicted by the projections may not be sufficiently robust to provide a basis for consensus-based management and they could be overly precise since some important sources of uncertainties currently remain unquantified [14]. An elicitation methodology was sought by Atlantic Wide Research Programme for Bluefin Tuna (GBYP) to capture stakeholder perceptions of each of the broad set of uncertainties that may be important to include in stock assessments of Atlantic bluefin tuna (*Thunnus thynnus)* and then to provide measures of their relative importance in terms of their impact on achieving management objectives.

The goals of this expert elicitation were both pragmatic and strategic: to establish the impact that each uncertainty represented for management; to rate the extent that the uncertainty could be reduced by further study; and to assess how much each uncertainty has already been represented in management models. The aim was to enable both a description of the scale of the problem arising from the various uncertainties and to quantify the potential for mitigation of risks posed by each source of uncertainty relative to current practice in producing the scientific advice. This would serve as a basis for prioritizing sources of uncertainty in order to facilitate future risk management actions. The historical basis for many of these uncertainties and the gaps in the current knowledge has been described by Di Natale [15]. Additionally, the degree of consensus among stakeholders on sources and scales of uncertainty was evaluated and tested in a targeted follow-up workshop. Finally, graphical tools were designed and provided to ICCAT to help scientists negotiate their own consensus on priorities, and take further steps to manage risks. A methodology was suggested to prioritize the identified uncertainties, based on analysis of the responses to the questionnaires. However, the resulting list of priorities was not intended to be prescriptive and ICCAT was encouraged to use the information to forge a consensus on their own plan of action for implementing risk based management.

The main sources of uncertainty in the management of Eastern Atlantic and Mediterranean bluefin were reviewed by Fromentin et al. [16] and the use of Management Strategy Evaluation (MSE) to develop long term management plans were discussed. MSE involves a number of steps [17] including: identification of management goals (and performance measures to quantify the extent to which those goals have been achieved); selection of hypotheses which impact on the risk of not achieving those goals; the development of Operating Models (OM), i.e. simulation models, to represent those hypotheses and the use of the OM to evaluate alternative management strategies. MSE can be a main part of risk based management.

The approach proposed here will provide the basis to develop a reduced number of scenarios that cover the main sources of uncertainty and concerns of stakeholders. Such an approach will facilitate the movement from qualitative to a quantitative methods and preserve both the breadth and the depth required within an Ecosystem Approach to Fisheries management [18].

2. Methods

A questionnaire was developed in spreadsheet format to elicit ratings of uncertainty from stakeholders for each of 33 risk-related processes, assumptions and hypotheses which were identified from literature review and consultation with experts and other stakeholders. Respondents were asked to provide scores for the 33 variables in each of three dimensions: importance of the variable; uncertainty of knowledge concerning the variable; and the degree to which that variable was represented in the current assessment. These dimensions were used because they describe those aspects of uncertainty that are relevant in a risk-based management framework: 'Could it make a difference?'; 'Is the problem tractable?'; 'To what extent has it already been tackled?'.

Most potential sources of uncertainty were identified through literature review [19, 20, 21, 22, 23]. The list of sources of uncertainties was further refined and extended during discussion with ICCAT scientists. The sources of uncertainty considered fell into eight categories: Reference points; Recruitment; Population structure; Model; Management; Life History traits; Environmental; Catch. Thirty-three sources of uncertainty were identified and evaluated. The choice of uncertainties to include in the questionnaire is important, especially when those developing the questionnaire had less experience of the case study than the respondents. Therefore as part of the process respondents were asked whether there were sources of uncertainty that were missing and whether certain sources of uncertainty were confounded. If there were important omissions then these could be followed up in an additional questionnaire. Correlations between sources of uncertainty are to be expected as stock assessment data sets seldom have sufficient information to be able to specify key processes impacting a population, which are also often not independent in nature. For example, in the bluefin assessment based on virtual population analysis, a lack of older fish in the plus group could be caused by older fish being less susceptible to capture or senescence. The consequences of either are quite different. Any indication of confounded uncertainties was noted so that they could be addressed in subsequent analyses.

The respondents included experts involved in stock assessment (n = 23), several NGOs (n = 4) which focus on Bluefin tuna, and a manager representing one of the fishing nations (n = 1); the elicitations were conducted at two GBYP ICCAT meetings in Madrid in June 2011 and September 2012. Considerable effort was made to get as many questionnaire responses as possible: questionnaires were officially presented at ICCAT meetings (two meetings of the Standing Committee on Research and Statistics (SCRS) meetings and one Commission meeting). The questionnaires have also been personally delivered in electronic version to all bluefin tuna scientists and to the Commissioners of all ICCAT Contracting Parties/Cooperating Entities (CPCs) concerned with the Atlantic bluefin tuna fisheries. In several cases, questionnaires and request for cooperation were delivered several times. Only one manager completed the questionnaire despite direct requests to all 47 contracting parties and the observers at the 18th Special Meeting of the International Commission for the Conservation of Atlantic Tunas, Agadir, Morocco (October 2012).

Before the elicitations were conducted, the respondents were given the context, method and purpose of the questionnaire. The motivation to complete and contribute to the questionnaire was that the results would be used to direct research funding, improve assessment and communicate uncertainty to the decision makers – all direct concerns for these respondents. The subjective opinions of the participants were of interest so possible individual bias related to issues of personal experience or concern was expected and accepted.

The survey was structured to present a base level of information on all issues identified in the literature review. Notes provided a shared context to each source of uncertainty and respondents were encouraged to consult these before answering the questions. The immediate graphical feedback provided by the elicitation tool gave respondents the opportunity to review and/or amend their answers accordingly. The questionnaires were completed individually and there was no opportunity for respondents to be influenced by the responses of others.

To understand the reasons for disagreements and explore the possibility of achieving consensus in a larger group, a focus group of five people (four scientists and an NGO representative) was conducted. Through a group discussion facilitated by risk analysts, a consensus opinion was sought for Importance, the most influential dimension of these uncertainties to risk management.

2.1 Components

For each source of uncertainty respondents were asked to evaluate three dimensions:

- Importance - potential impact on management goals
- Knowledge - potential to reduce uncertainty through more research
- Representation in current assessments

For each uncertainty, the three dimensions were rated on a scale (from very low to very high) such that the end of the scale corresponded to a greater risk, either greater importance, greater lack of knowledge or greater lack of representation.

2.1.1 Importance

Importance was rated in terms of the potential impact (minimal, minor, moderate, major, or massive) that a particular process/assumption/hypothesis (source of uncertainty) could have on achieving management objectives.

2.1.2 Knowledge

In the second dimension the concern was epistemological uncertainty or the potential to reduce uncertainty with greater knowledge. It was rated as follows:

Very low - the value of the variable is very well understood

Low - the value of the variable is extensively researched

Medium - the value of the variable is moderately well understood

High - the value of the variable is poorly understood

High uncertainty - there is little of no information about the variable

2.1.3 Representation

The third dimension asked how well a particular source of uncertainty was represented in the assessment or scientific advice. This question elicits the extent to which a given source of uncertainty is already taken into account in the assessment:

Very well represented - full distribution of uncertainty has been integrated into the assessment methodology

Well represented - some percentile values have been used

Represented - some sensitivity analysis or MSE evaluation has been done

Poorly represented - uncertainty in the variable is not considered (deterministic)

Very poorly represented or not at all - the variable has not (or barely) been represented or considered in the assessment

2.2 Visualization

An important objective was to present the data in the form of interactive visualizations and to use multiple types of representation adjusted to the user needs [24]. A visualization method designed for ICCAT was based on risk assessment techniques developed in the EC FP7 project PRATIQUE (to improve Pest Risk Analysis in agriculture) and adopted by the European and Mediterranean Plant Protection Organisation (EPPO) [25, 26, 27]. The three components of risk, described in the previous section, are visualized in terms of variously sized bubbles (Fig. 1.) located in a two dimensional space defined by 'importance' and 'representation' components. The size of the bubble portrays the degree of knowledge-related uncertainty; small size depicts low uncertainty, the size of the bubble increases as uncertainty increases. The background of the bubble chart is colored from green (bottom left) through yellow\orange to red (top right); green indicating lower risk area of the chart and red indicating higher risk. In this visualization method, color and size provide a relative view, not linked to specific risk preferences or judgments. This visualization forms an integral part of the elicitation tool, providing instant feedback to the respondent of the overall implications of their beliefs about various sources of uncertainties.

[FIG.1 ABOUT HERE]

3. Results

3.1 Raw data visualization

Data from each of the respondents was collated in a spreadsheet and presented in two ways:

a) Bar charts, in which the variables were grouped according to eight types (Management, Biology, Environment and Model). For each variable the distribution of respondent scores is shown for the three dimensions of Importance, Knowledge uncertainty and Representation (Figs. 2, 3 and 4, respectively).

Hoop diagrams which have a similar format to those shown in Fig. 1 except that hoops, instead of opaque bubbles, were used to allow all responses to be seen superimposed in the same chart (examples shown in Fig. 5). Green color represents NGO answers, blue – managers, black – scientists.

3.1.1 Bar chart visualization

Bar charts presented in Figures 2, 3, and 4 enable a quick overview of the partition of the total number of responses for each source of uncertainty grouped into categories (Reference points, Recruitment, Population structure, Model, Management, Life History Traits, Environmental, Catch). These are displayed in separate figures for each of the dimensions (Importance, Knowledge, and Representation). In these figures the respondents are considered as a single group. The answers are color-coded so that both dominating attitudes and a consensus can be apparent at a glance. For example, looking at Figure 2, at the last question regarding catch-under-reporting, it is clear that all of the respondents thought that its importance was moderate, major or massive, because both yellow and green colors are absent, and that the latter two categories dominate. Looking at Figure 3 as a whole, red spectrum colors indicate all sources of uncertainty are seen to be relatively important. Similarly, Figures 3 and 4 show that for all sources of uncertainty at least some experts think that the knowledge and representation of uncertainty in each variable is insufficient.

[FIGS. 2, 3 AND 4 ABOUT HERE]

3.1.2 Hoop diagram visualization

The hoop diagrams are a powerful tool for displaying the degree of consensus among experts within each variable in each of the three dimensions. For example, for “Natural mortality” there is a high degree of consensus regarding the high Importance, poor Knowledge uncertainty and poor Representation in the current assessment as indicated by consistently large hoops and that the hoops occupy the upper right (high risk) quadrant of Figure 5a. For “Interactions with other species”, there is a high consensus with respect to Knowledge uncertainty and poor Representation (in the current assessment) but there was very little agreement about the Importance of this variable (Fig. 5b). In Figure 5c, there is high consensus with regard to Knowledge uncertainty and Importance but very little agreement on how well this variable (Stationarity, cohort year effects, density) is included in the current assessment. The variety of hoop sizes and the scattering of hoops in Figure 5d show how the experts had little consensus in any dimension when asked about the Risk Attitudes of Managers.

[FIG. 5 ABOUT HERE]

3.2 Correlations between variables

The scores of the three variables (Importance, Knowledge uncertainty and lack of Representation) assigned by each expert were, in varying degrees, not independent. To illustrate this, pairwise Spearman rank correlation was performed on the scores provided by each assessor. The histograms (Fig. 6) show the distribution of correlation coefficients for the group of assessors. There was a tendency for most, but not all, experts to score Importance variables also as Knowledge uncertain. No causation is implied by the correlations themselves and it could be that greater perceived Knowledge uncertainty contributed to the reason that assessors also scored the Importance variable highly. The majority also tended to score the Importance variables as slightly more poorly for Representation in the model but the spread of perceptions was wide on this point. Almost all experts scored the lowest ranked Representation variables as the lowest on Knowledge uncertainty.

[FIG. 6 ABOUT HERE]

3.3 Prioritization of uncertainties

Using both the consensus score of Importance obtained from the sub-group of five individuals and the overall responses, an action plan was formulated in consultation with the GBYP modelers of what prioritization should be given to the quantitative testing of the uncertainties. The resulting list of priorities is subject to computational constraints as some variables are more difficult to translate into scenarios for MSE or to incorporate into an existing stock assessment model. Figure 7 presents the group of 20 variables assessed by the panel as being of either massive or major Importance, the figure also includes the hoop graphics from the individual elicitations.

[FIGURE 7 ABOUT HERE]

4. Discussion

Development of techniques to interact with a range of stakeholders is a response to the need to elicit and express the differences in ideas or objectives held by those who advise, decide, comply with, participate in and are ultimately affected by fisheries management. This is part of an increasingly inclusive approach to the management of environmental resources but also an acknowledgement of the failure of management approaches that ignored uncertainty and diversity of knowledge that has led to poor outcomes for both stocks and fishers worldwide. Enabling stakeholders to express their opinions reveals how diverse those opinions can be even within a relatively small group of stakeholders who have been focused together for years on a particular stock such as within the ICCAT Eastern Bluefin Tuna stock assessment group. Providing tools for structuring, eliciting and visualizing the differences allows those differences to be analyzed, negotiated and possibly resolved. Effective elicitation is a prerequisite for any opportunity for inclusive consensus. However, inclusive consensus may not be a shared goal or other political considerations may interfere with elicitation efforts. A lack of trust in the process of how information may be used might have deterred some managers while others may have been preoccupied with other business. The reason for the low participation of managers is unclear, yet it seems to be specific to ICCAT's situation, as in other elicitation efforts conducted by the authors, such as for the Baltic and North Sea fisheries, access to managers' views achieved a response rates similar to that of scientists.

The instantaneous graphical feedback provided in the questionnaire may improve consistency of subjective judgments as well as stimulate, within an individual, formation of a broader and better structured understanding of uncertainties. Lipkus and Hollands [28], reviewing elicitation methodology, note that 'Visual representations may substantially improve comprehension of risk and make expert consultations more efficient'. Visualization provides not just an immediate feedback, but a sense of satisfaction in being able to express, define, and represent in some way the feelings of ignorance, frustration and ambiguity. Codifying uncertainty visually is empowering, making the elicitation process more efficient and effective for both elicitors and respondents.

Elicitation of uncertainties fits logically within a risk analysis framework. Risk analysis is a formal process in which risks are identified, assessed, prioritized, managed and communicated to ensure that management objectives can be more effectively and efficiently met. In this paper an initial scoping stage of Risk Analysis is presented, providing a basis by which to prioritize effort to quantify high-priority risks whenever possible. One such method is Management Strategy Evaluation (MSE). In MSE, the need for care in representing uncertainties and for thorough documentation of the elicitation process has been highlighted by both Rochet and Rice [29] and Butterworth et al. [30]. The methodology outlined here contributes to this documentation process by characterizing perceptions of uncertainties by graphical methods.

In the analysis, no weighting was given to the views of individuals based on their experience nor were they challenged on their responses as they would be for example in the Delphi Method [31]. A reason for this was because in this study we were primarily concerned in understanding the current viewpoints of stakeholder prior to conducting MSE. This was to help ensure that the MSE considered the legitimate concerns of stakeholder and then to observe how these viewpoints changed after conducting quantitative analyses to assess the actual impacts on management objectives. A strength of MSE is that it should add stability to the management decision process as management objectives (and how to evaluate how well alternative management procedures meet them given uncertainty) are agreed through a dialogue between scientists, managers and stakeholders [32, 33, 16]. Recording how stakeholders' views change after conducting an MSE will therefore provide a valuable insight into the management and the MSE process.

Quantification of uncertainties is both a labor and a computationally demanding process and thus its efficiency hinges on prioritization. The sub-group discussion of the elicitation results described in this paper is one of many possible options for prioritization. Though a small group inevitably introduces some bias, facilitation of a structured discussion based on the wider group elicitation minimizes this. Lack of consensus in various dimensions might play a greater role in determining the prioritization in future exercises or alternatively attempts to achieve consensus can be made before proceeding to quantification stages of Risk Analysis. In this exercise the causes of lack of consensus in important variables was identified and addressed through stakeholder discussion facilitated by risk analysts. Understanding the reasons for low consensus can lead to improved consensus and improved prioritization of uncertainties within the modeling framework. This approach was tested with a subset of five experts who were indeed able to agree on a common rating for the Importance dimension of variables (Fig. 7).

Given that the combinations of scenarios for inclusion in an MSE grow exponentially with each extra variable, it will not be possible to evaluate the quantitative impact of all sources of uncertainties included in Figure 7. Discussions with modelers are needed to reduce the twenty uncertainties to a shorter initial list of those variables most amenable for further evaluation, Simpler interactive modeling approaches will be valuable in doing this. For example by using a deterministic OM (without the need to run Monte Carlo simulations) where the preferences of the different stakeholder groups are modeled as utility functions [34, 35]. This will allow the impact of the different sources of uncertainty to be investigated by reference to a change in utility. Once it is determined which of the uncertainties have the greatest impact on the utility function discussions can be initiated with the stakeholders to elicit which interactions among the 20 shortlisted uncertainties should have priority for further quantitative investigations. Finally, a representative ‘reference’ set of operating models can be selected based on analysis of interactions among uncertainties. The plausibility weights for this reference set of OMs provide another opportunity to engage stakeholders, and to elicit their views as to how robustness trials with the MSE should be ‘tuned’. Having thus established an MSE framework, other sources of uncertainty from Figure 7 can be quantitatively addressed but it is still unlikely that every source of uncertainty identified in the qualitative stage described in this paper can be given a quantitative treatment. So elicitation process also serves to document what is missing from the quantitative risk assessment, giving decision makers a more transparent and comprehensive view of uncertainties in the scientific advice to managers and other stakeholders.

MSE is a complex and time consuming process and simpler quantitative methods for identifying the relative impact of the different sources of uncertainty to reduce the number of scenarios to be considered have obvious appeal. For example elasticity analysis, where the proportional change of the key operating model (OM) outputs, summarized in an objective function, is calculated relative to changes in the input variable or a base-case scenario. Having determined which of the uncertainties have greater impact on the objective function in the elasticity analysis, discussions can be initiated with the stakeholders to elicit which interactions among the 20 shortlisted uncertainties should have priority for further quantitative investigations. Finally, a representative ‘reference’ set of operating models can be selected based on analysis of interactions among uncertainties. The plausibility weights for this reference set of OMs provide another opportunity to engage stakeholders, and to elicit their views as to how robustness trials with the MSE should be ‘tuned’. Having thus established an MSE framework, other sources of uncertainty from Figure 7 can be quantitatively addressed but it is still unlikely that every source of uncertainty identified in the qualitative stage described in this paper can be given a quantitative treatment. So elicitation process also serves to document what is missing from the quantitative risk assessment, giving decision makers a more transparent and comprehensive view of uncertainties in the scientific advice to managers and other stakeholders.

Acknowledgments

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Figure captions

Fig. 1. Visualising responses by individual experts: a) example of **Lowest risk** extreme characterised by being of minimal Importance, Very well represented in the assessment and very low knowledge uncertainty. The Bubble consequently occupies the low risk bottom-left green zone; b) **Highest risk** extreme caused by massive Importance, very poorly Represented in the Assessment, and very high Knowledge uncertainty. The Bubble occupies the upper-right red zone indicating a high priority variable.

Fig. 2. Bar chart of responses to Importance component of each variable, hypothesis and assumption.

Fig. 3. Bar chart of responses to Knowledge uncertainty component of each process, hypothesis and assumption.

Fig. 4. Bar chart of responses to Representation component of each process, hypothesis and assumption.

Fig. 5. (a) Environmentally driven recruitment variability and density dependence: high consensus on Importance and that it is also poorly Represented in the current assessment, with high agreement on Knowledge uncertainty; (b) Interactions with other species: high consensus on the lack of Representation in current assessment, moderate agreement on degree of Knowledge uncertainty but very low consensus on the Importance of this variable; (c) Stationarity, cohort

year effects, density: High consensus on Importance and low consensus on the Representation in current assessment, but general agreement on high Knowledge uncertainty; (d) Risk attitudes of managers: Low consensus in all dimensions.

Fig. 6. Distributions for 28 experts of the correlation coefficients between their scores for (a) Importance vs. Knowledge uncertainty; (b) Importance vs. Representation; (c) Knowledge uncertainty vs. Representation. Individual correlations have a significant relationship where $r > 0.317$ ($P < 0.05$), bins shaded grey contain only significant relationships.

Figure 7. 20 variables assessed by the panel as being of either massive or major Importance, the figure includes the hoop graphics from the individual elicitations. For simplicity, the vertical and horizontal scales are not presented here but follow the same axes descriptions and scales as for Figures 1 and 5.

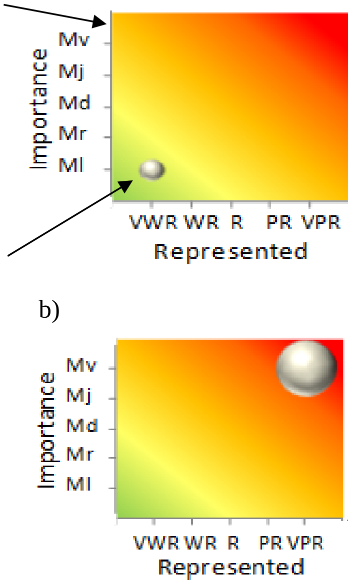
Figure 1 (in native Excel format)

Figure 1. Color in print; Color in electronic version

Vertical-axis shows the **Importance** dimension on a scale of Minimal (Ml), Minor (Mr), Moderate (Md), Major (Mj), Massive (Mv).

Size of bubble shows **Uncertainty** rating. This small bubble denotes low uncertainy and larger bubbles denote higher uncertainty levels.

a)



The horizontal-axis shows how well the variable is **Represented in the current assessment**. Very Well Represented (VWR) to Very poorly represented or not at all (VPR)

Figure 2 (in native Excel format)

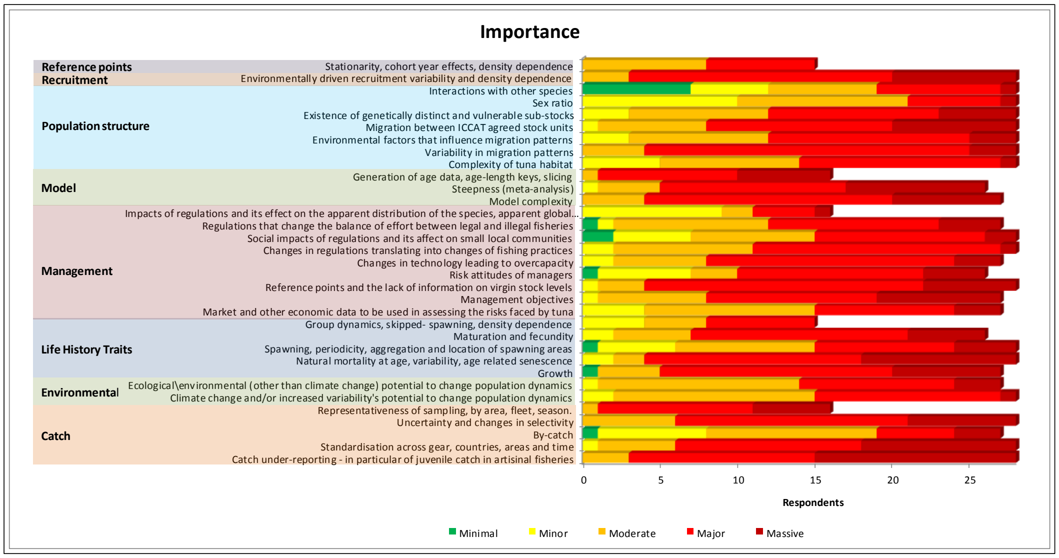


FIGURE 2. **Color in print; Color in electronic version**

Figure 3 (in native Excel format)

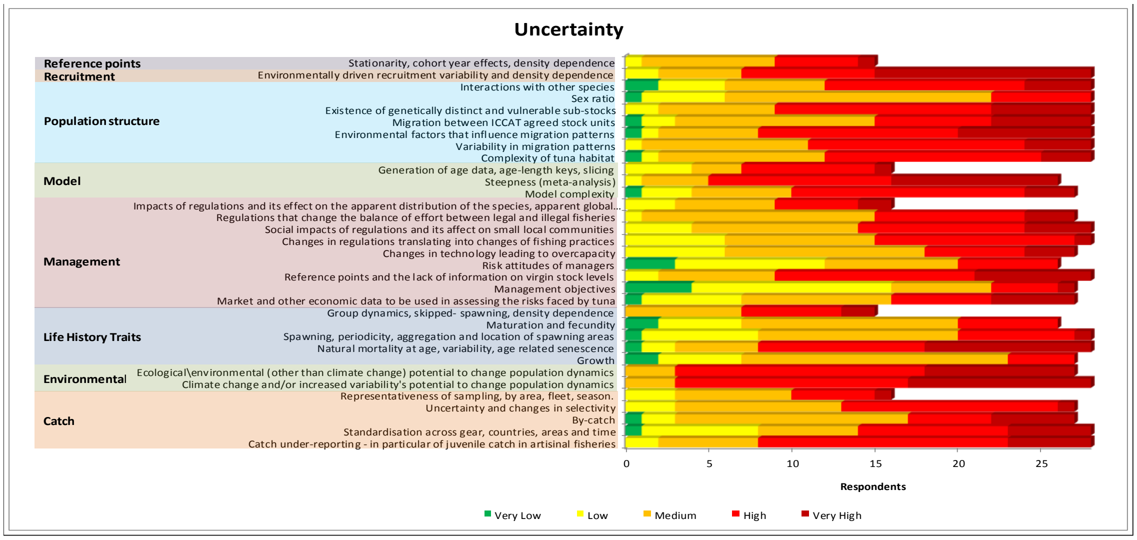


FIGURE 3. **Greyscale in print; Color in electronic version**

Figure 4 (in native Excel format)

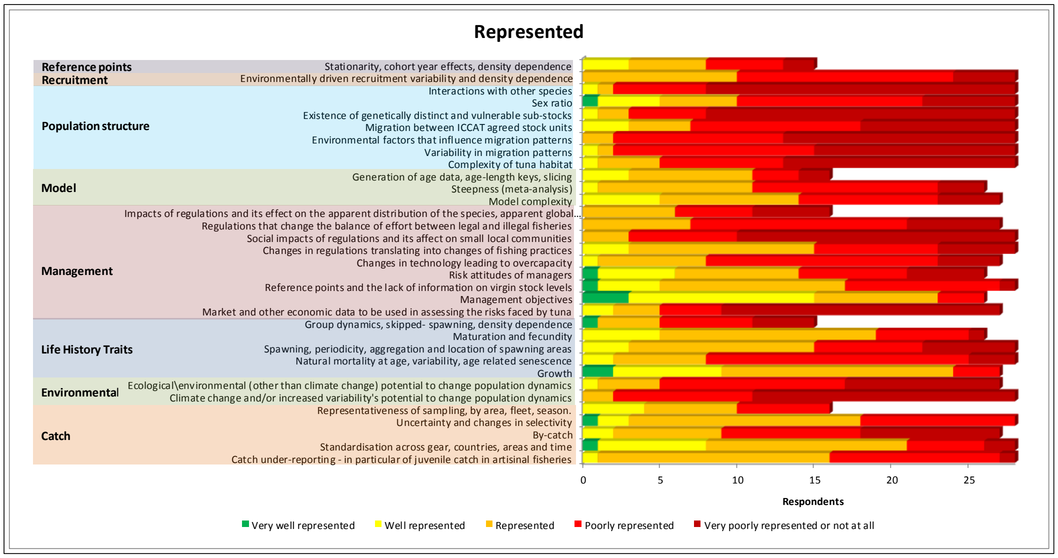


FIGURE 4. **Greyscale in print; Color in electronic version**

Figure 5 (in native Excel format)

Figure 5. Color in print; Color in electronic version

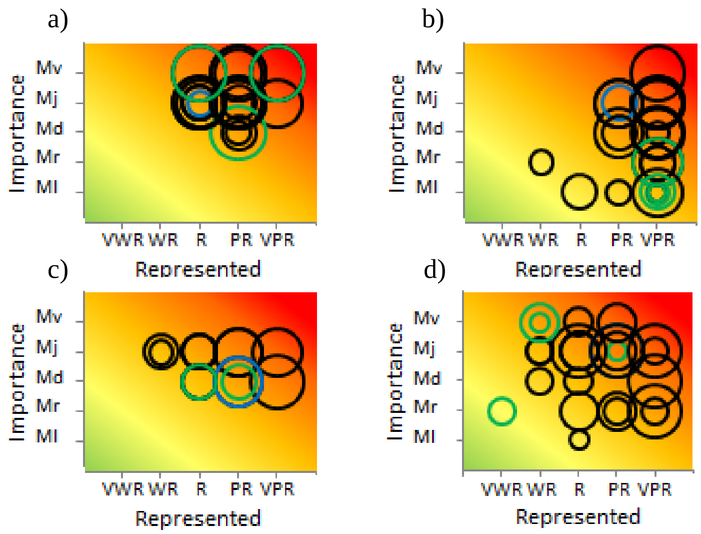


Figure 6 (in TIFF format)

Click here to download high resolution image

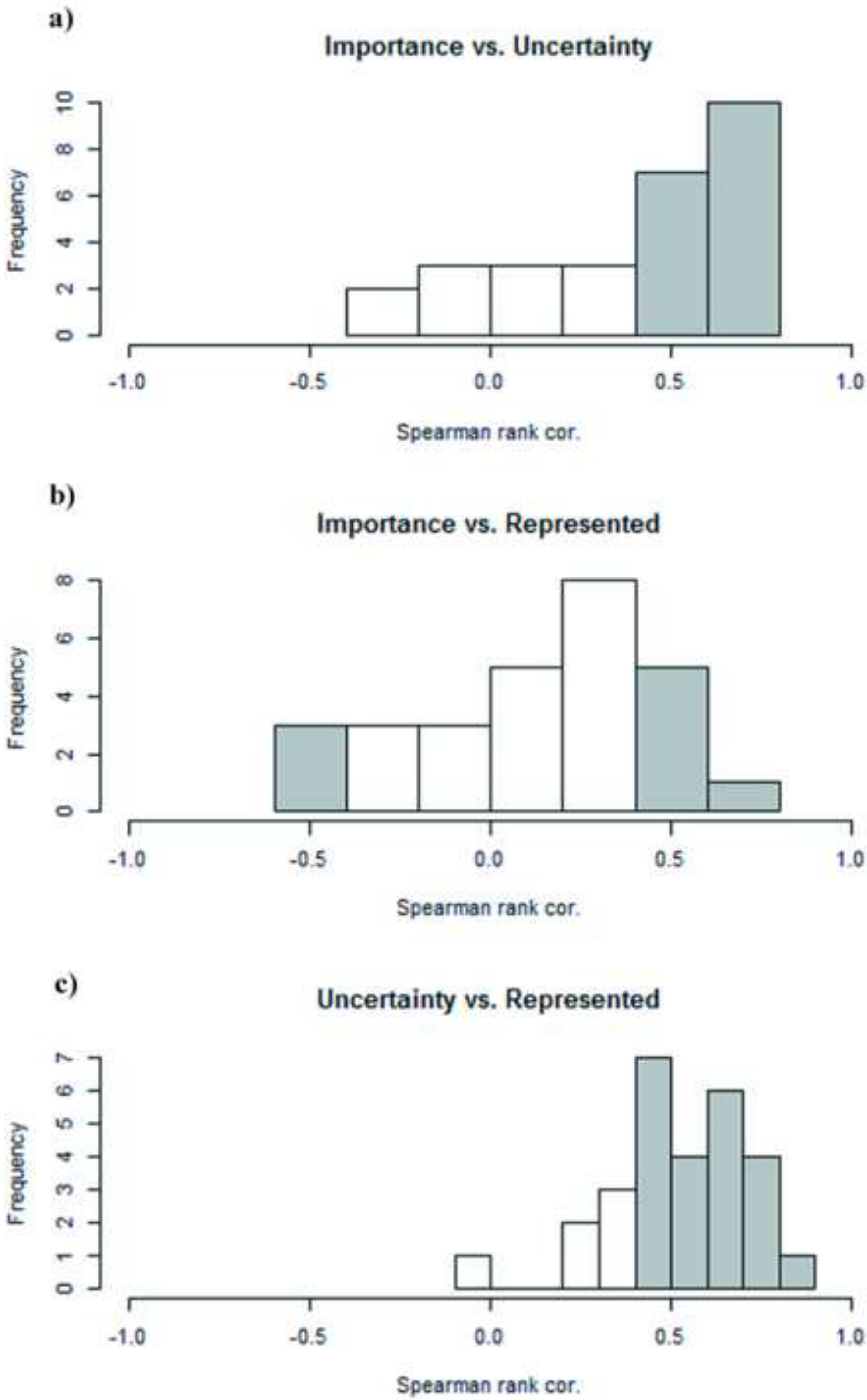


Figure 7 a (in native Excel format)

Figure 7 a - Print in Greyscale; Color in electronic version

a)

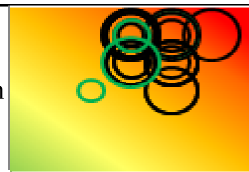
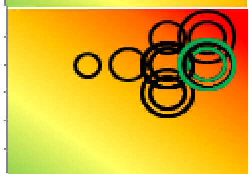
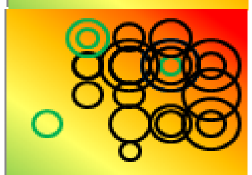
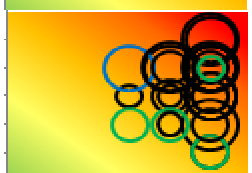
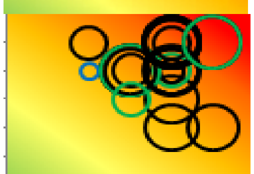
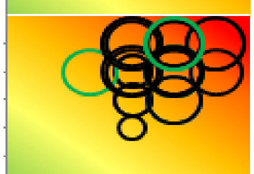
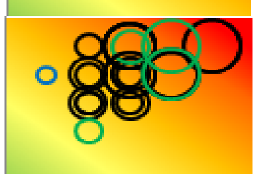
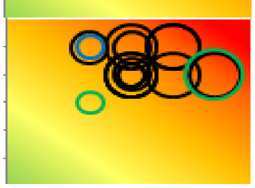
Variable	Individual elicitations	Group consensus on *Importance*
Catch under-reporting - in particular of juvenile catch in artisinal fisheries		Massive
Variability in migration patterns		Massive
Risk attitudes of managers		Massive
Social impacts of regulations and its affect on small local communities		Massive
Environmentally driven recruitment variability and density dependence		Major
Natural mortality at age, variability, age related senescence		Major
Steepness (meta-analysis)		Major
Standardisation across gear, countries, areas and time		Major
Generation of age data, age-length keys, slicing		Major

Figure 7 b (in native Excel format)

Figure 7 b - Print in Greyscale; Color in elect. version

b)

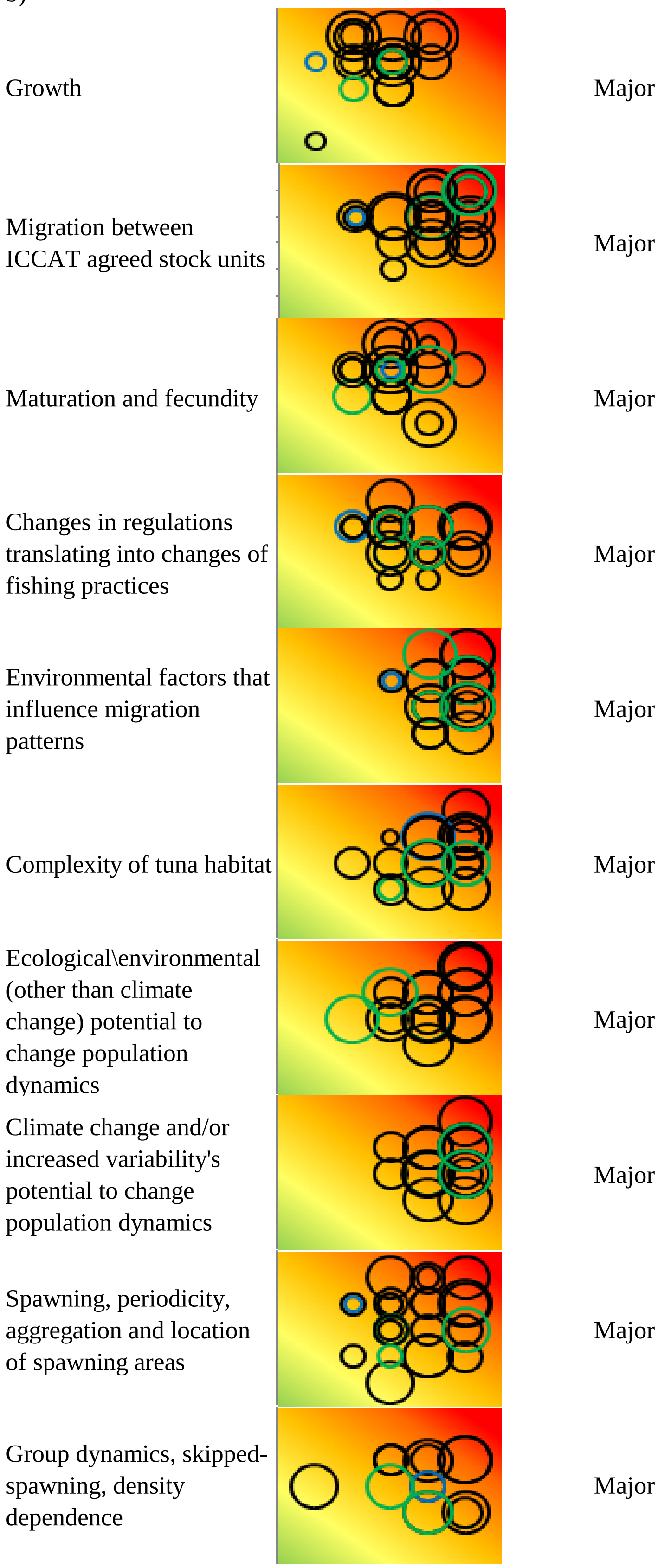
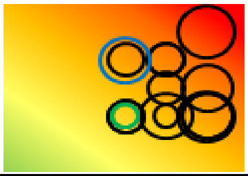


Figure 7 c (in native Excel format)

Table 1 c - Print in Greyscale; Color in electronic version

c)

Impacts of regulations and its effect on the species' apparent global distribution.		Major