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 formalise the process of elicitation of uncertainties, from both experts and stakeholders, for the International Commission for the Conservation of Atlantic Tunas (ICCAT). The aim of the elicitation was to identify and prioritise uncertainties for inclusion in Operating Models for Management Strategy Evaluation (MSE). The tool presented in this paper supports the qualitative prioritisation of uncertainties, while also visualising 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.

Key words: stock assessment; risk analysis; uncertainty; expert elicitation; visualization; Bluefin tuna

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 (Garcia and Charles 2008). Accounting for uncertainty through risk-based management has been a goal of fisheries management for some time (Hillborn et al. 2001), first formalised as 'the precautionary approach' by FAO (1996). 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 (Fletcher 2005).

Risk analysis[1] is a process in which risks are identified (scoped), assessed, managed and communicated (Australian and New Zealand Standard Risk Analysis Standards Australia, 2004, FAO 2004, ISO 31000:2009). In a fisheries context, Fletcher et al. (2002) detail the entire (ecological) risk assessment process while in Fletcher (2005) he focuses 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 (Fletcher 2005, Rochet and Rice 2005) and other fields (Burgman 2005, Black et al. 2010). These methods may include interviews, workshops, repeatable performance feedback and questionnaires, all designed to ensure that experts give consistent responses (Keeney and von

[1] The terms risk assessment and risk analysis have been used interchangeably in various standards, so ISO 31000:2009 includes risk analysis as a sub-component of the risk assessment process whereas FAO (2004) 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 we will use the term risk analysis as the overarching description of a procedure which includes concern (identification), assessment, management and communication.

Winterfeldt 1991, McBride and Burgman 2012). Methods usually emphasise the need to elicit information in such a way that the reasoning behind the judgements are transparent and that these judgements are given on the basis of all relevant information (McBride and Burgman 2012). 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 visualisation in the representation of uncertainty. This paper employs a novel 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) Atlantic Wide Research Programme for Bluefin Tuna (GBYP) rebuilding plan uses stochastic projections that do not currently capture all the uncertainty associated with stock assessment/management variables (GBYP 2011). The stock assessment and catch quota outcomes predicted by the projections may not be sufficient to provide a basis for consensus-based management and they could be over optimistic (GBYP 2011). An elicitation methodology was sought by GBYP to capture stakeholder perceptions of each of the broad set of uncertainties that may be important to include in stock assessments of Bluefin tuna *Thunnus thynnus* (Linnaeus 1758) 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. 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.

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 provides 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 (Fromentin and Powers 2005, Fromentin 2006, Kell and Fromentin 2007, Fromentin and Kell 2007, CITES 2010). 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.

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.

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. Finally, immediate graphical feedback provided the participants with the opportunity to verify or amend their answers accordingly.

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.

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.

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.

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

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

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 (Spiegalhalter et al. 2011). A novel visualisation 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) (Baker et al. 2009, Holt et al. 2012, Mumford et al. 2011). 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 coloured 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, colour 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.

RESULTS

Raw data visualisation

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).
b) 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 colour represents NGO answers, blue – managers, black – scientists.

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 colour-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, we can immediately tell that all of the respondents thought that its importance was moderate, major or massive, because both yellow and green colours are absent, and that the latter two categories dominate. Looking at Figure 3 as a whole, red spectrum colours 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.

Hoop diagram visualisation

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, we see 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.

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.

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 modellers 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. Table 1 presents the group of 20 variables assessed by the panel as being of either massive or major Importance, the table also includes the hoop graphics from the individual elicitations.

DISCUSSION

Development of novel 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 visualising the differences allows those differences to be analysed, negotiated and possibly resolved. Effective elicitation is a prerequisite for any opportunity for inclusive consensus.

The instantaneous graphical feedback provided in the questionnaire may improve consistency of subjective judgements as well as stimulate, within an individual, formation of a broader and better structured understanding of uncertainties. Lipkus and Hollands (1999), reviewing elicitation methodology, note that ‘Visual representations may substantially improve comprehension of risk and make expert consultations more efficient’. Visualisation 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 we present an initial scoping stage of Risk Analysis, providing a basis by which to prioritise 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 (2009) and Butterworth et al. (2010). The methodology outlined here contributes to this documentation process by characterising perceptions of uncertainties by graphical methods.

Quantification of uncertainties is both a labour and a computationally demanding process and thus its efficiency hinges on prioritisation. The sub-group discussion of the elicitation results described in this paper is one of many possible options for prioritisation. Though a small group inevitably introduces some bias, facilitation of a structured discussion based on the wider group elicitation minimises this. Lack of consensus in various dimensions might play a greater role in determining the prioritisation 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 prioritisation of uncertainties within the modelling 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 (Table 1).

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 Table 1. Discussions with modellers are needed to reduce the twenty uncertainties to a shorter initial list of those variables most amenable for further evaluation, Simpler interactive modelling 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 modelled as utility functions (Houthakker 1950, Rosenberg and Restrepo 1994) 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 Table 1 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.

Röckmann et. al. (2012) showed that extensive discussions between scientists and stakeholders were an important precursor to creating the atmosphere of goodwill required to openly address uncertainties in a participatory, transparent, clear and understandable manner. MSE requires several steps (Punt and Donovan 2007), including choosing hypotheses about stock and fleet dynamics to simulate to evaluate alternative Management Strategies. If stakeholders do not agree on the importance of the hypotheses chosen then it will be impossible to agree on what management strategy to adopt. The elicitation approach presented in this paper is therefore a potentially useful approach when using MSE to develop management frameworks.

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LITERATURE CITED

AS/NZS 4360:2004. 2004. Risk management. Standards Australia and Standards New Zealand, 2004.

Baker, R., A. Battisti, J. Bremmer, M. Kenis, J. Mumford, F. Petter, G. Schrader, S. Bacher, P. De Barro, P. E. Hulme, O. Karadjova, A. O. Oude Lansink, O. Pruvost, P. Pyšek, A. Roques, Y. Baranchikov and J. H. Sun. 2009. PRATIQUE: a research project to enhance pest risk analysis techniques in the European Union. Bulletin OEPP/EPPO Bulletin 39: 87–93.

Black, J., E. J. Milner-Gulland, N. Sotherton, S. Mourato, S. 2010. Valuing complex environmental goods: landscape and biodiversity in the North Pennines. Environmental Conservation 37:136–146

Burgman, M. A. 2005. Risks and decisions for conservation and environmental management. Cambridge University Press, Cambridge.

Butterworth, D. S., N. Bentley, J. A. A. De Oliveira, G. P. Donovan, L. T. Kell, , A. M. Parma, , A. E. Punt, K. J. Sainsbury, A. D. M. Smith and T. K. Stokes. 2010. Purported flaws in management strategy evaluation: basic problems or misinterpretations? ICES Journal of Marine Science 67:567–574.

CITES (2010). Proposal to include Atlantic Bluefin Tuna (Thunnus thynnus (Linnaeus, 1758)) on Appendix I of CITES in accordance with Article II 1 of the Convention. Consideration of Proposals for amendment of Appendices I and II. Convention on International Trade in Endangered Species of Wild Fauna And Flora, fifteenth meeting of the Conference of the Parties Doha (Qatar), 13-25 March 2010. CoP15 Prop. 19. pp. 34. http://www.cites.org/eng/cop/15/prop/E-15-Prop-19.pdf (last accessed 11 November 2013).

FAO. 1996 Precautionary Approach to Capture Fisheries and Species Introductions, Elaborated by the Technical Consultation on the Precautionary Approach to Capture Fisheries (Including Species Introductions) (6–13 June 1995, Lysekil, Sweden), FAO Technical Guidelines for Responsible Fisheries, No. 2, FAO, Rome.

FAO. 2004 International Standards for Phytosanitary Measures, ISPM No. 11 Pest Risk Analysis for Quarantine Pests. Including Analysis of Environmental Risks and Living Modified Organisms. FAO, Rome.

Fletcher, W. J., J. Chesson, M. Fisher, K. J. Sainsbury, T. Hundloe, A. D. M. Smith, B. , B. Whitworth. 2002. National ESD reporting framework for Australian Fisheries: the 'How to' guide for wild capture fisheries. Fisheries Research and Development Corporation Final Report, Project No. 2000/145, Canberra, Australia, ASBN 1877098019

Fletcher, W. J. 2005. The application of qualitative risk assessment methodology to prioritize issues for fisheries management. ICES Journal of Marine Science 62:1576-1587.

Fromentin, J.-M. 2006. ICCAT Manual: Chapter 2.1.5: Atlantic Bluefin Tuna. pp 1-19. http://www.iccat.es/Documents/SCRS/Manual/CH2/2_1_5_BFT_ENG.pdf (last accessed 11 Nov 2013).

Fromentin, J.-M. and L. T. Kell. 2007. Consequences of variations in carrying capacity or migration for the perception of Atlantic bluefin tuna (*Thunnus thynnus*) population dynamics. Canadian Journal of Fisheries and Aquatic Sciences 64:827-836.

Fromentin, J.-M. and J. E. Powers. 2005. Atlantic bluefin tuna: population dynamics, ecology, fisheries and management. Fish and Fisheries 6:281-306.

Garcia, S.M. and A. T. Charles. 2008. Fishery systems and linkages: implications for science and governance. Ocean & Coastal Management 51:505-527.

GBYP (2011). Terms of Reference – Call for Tenders – GBYP 04/2011. Stock Assessment Modelling (ICCAT/GBYP Phase 2 – 2011). pp. 4. http://www.iccat.int/Documents/CFT/954-11_ENG.pdf (last accessed 11 Nov 2013).

Hillborn, R., J. J. Maguire, A. M. Parma and A. A. Rosenberg. 2001. The Precautionary Approach and risk management: can they increase the probability of successes in fishery management? Canadian Journal of Fisheries and Aquatic Sciences 58:99-107.

Holt, J., A. W. Leach, J. D. Knight, D. Griessinger, A. MacLeod, D. J. van der Gaag, G. Schrader, and J. D. Mumford. 2012. Tools for visualising and integrating pest risk assessment ratings and uncertainties, Bulletin OEPP/EPPO Bulletin 42:35-41.

Houthakker, H. S. 1950. Revealed preference and the utility function. Economica 17:159-174.

ISO 31000:2009. 2009. Risk management—Principles and guidelines.

Kell, L. T. and J.-M. Fromentin. 2007. Evaluation of the robustness of maximum sustainable yield based management strategies to variations in carrying capacity or migration pattern of Atlantic Bluefin tuna (*Thunnus thynnus*). Canadian Journal of Fisheries and Aquatic Sciences 64:837-847.

Keeney, R. L. and D. von Winterfeldt. 1991. Eliciting probabilities from experts in complex technical problems. IEEE Transactions on Engineering Management 38:191–201

Lipkus, I. M. and J. G. Hollands. 1999. The visual communication of risk. Journal of the National Cancer Institute Monographs 25:149–163.

McBride, M. F. and M. A. Burgman, M. A. 2012. Chapter 2 What Is Expert Knowledge, How Is Such Knowledge Gathered, and How Do We Use It to Address Questions in Landscape Ecology? In: Expert Knowledge and Its Application in Landscape Ecology. Perera, A. H., D. C. Ashton, C. J. Johnson (Eds.), Springer. ISBN 978-1-4614-1034-8.

Mumford, J. D., O. Booy, R. H. A. Baker, M. Rees, G. H. Copp, K. Black, J. Holt, A. W. Leach and M. Hartley. 2010. Invasive non-native species risk assessment in Great Britain. Aspects of Applied Biology 104:49-54.

Punt, A. E. and G. P. Donovan. 2007. Developing management procedures that are robust to uncertainty: lessons from the International Whaling Commission. ICES Journal of Marine Science: Journal du Conseil 64:603-612.

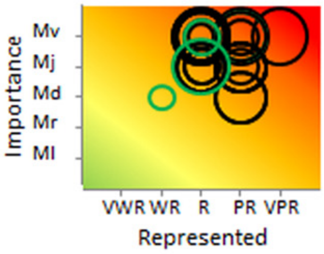
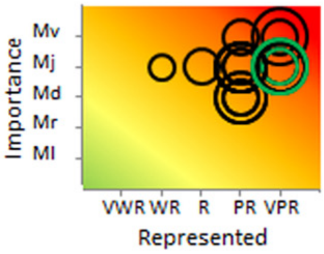
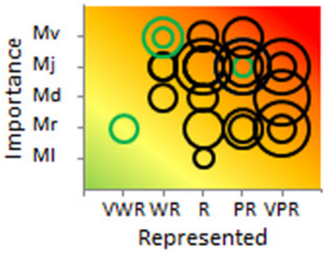
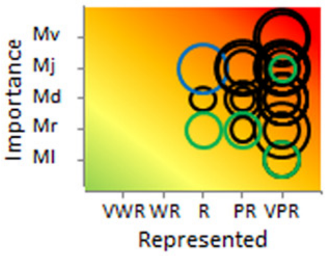
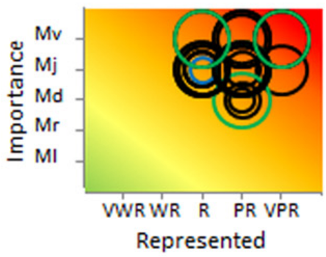
Rochet, M.-J. and J. C. Rice. 2005. Do explicit criteria help in selecting indicators for ecosystem-based fisheries management? ICES Journal of marine Science 62:528-539

Rochet, M.-J. and J. C. Rice. 2009. Simulation-based management strategy evaluation: ignorance disguised as mathematics? ICES Journal of Marine Science 66:754–762.

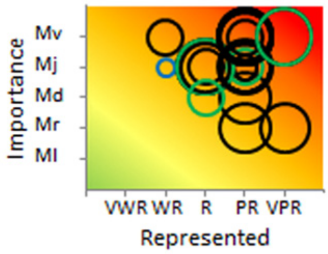
Röckmann, C., C. Ulrich, M. Dreyer, E. Bell, E. Borodzicz, P. Haapasaari, K. H. Hauge, D. Howell, S. Mäntyniemi, D. Miller, G. Tserpes, M. Pastoors. 2012. The added value of participatory modelling in fisheries management–what has been learnt? Marine Policy 36: 1072-1085.

Spiegalhalter, D., M. Pearson and I. Short. 2011. Visualizing Uncertainty About the Future. Science 333:1393-1400.

Table 1. 20 variables assessed by the panel as being of either massive or major Importance, the table includes the hoop graphics from the individual elicitations.

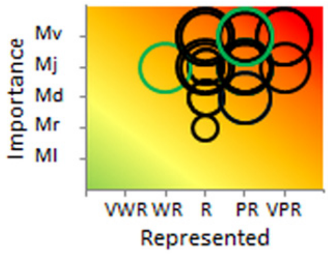
Variable	Individual elicitations	Group consensus on *Importance*
Catch under-reporting - in particular of juvenile catch in artisinal fisheries		Massive
Variability in migration patterns		Massive
Risk attitudes of managers		Massive
Social impacts of regulations and its affect on small local communities		Massive
Environmentally driven recruitment variability and density dependence		Major

Natural mortality at age, variability, age related senescence



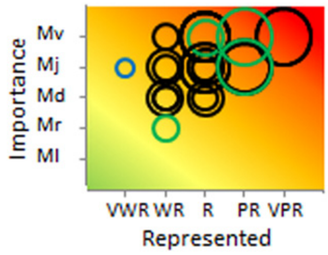
Major

Steepness (meta-analysis)



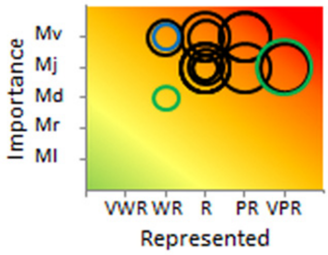
Major

Standardisation across gear, countries, areas and time



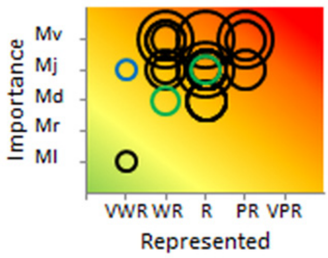
Major

Generation of age data, age-length keys, slicing



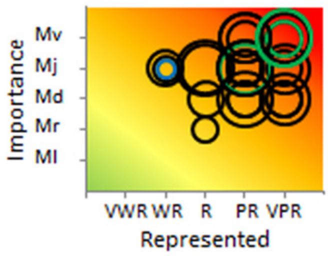
Major

Growth



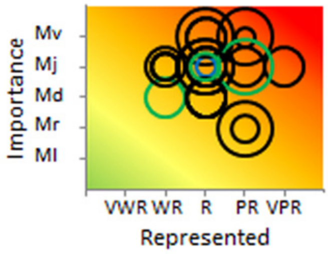
Major

Migration between ICCAT agreed stock units



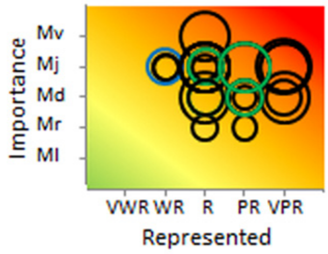
Major

Maturation and fecundity



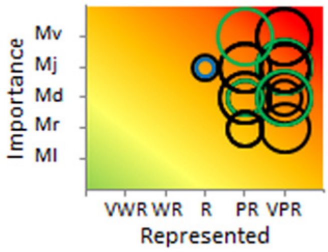
Major

Changes in regulations translating into changes of fishing practices



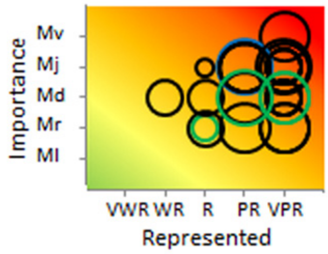
Major

Environmental factors that influence migration patterns



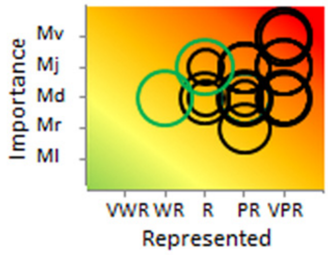
Major

Complexity of tuna habitat



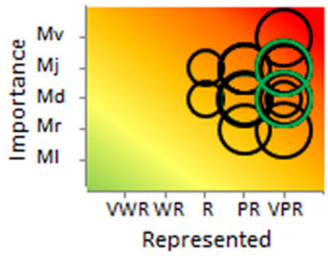
Major

Ecological\environmental (other than climate change) potential to change population dynamics



Major

Climate change and/or increased variability's potential to change population dynamics



Major

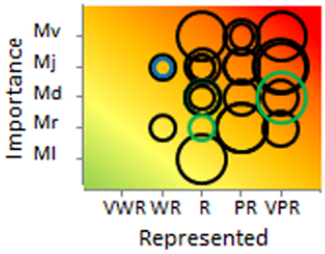
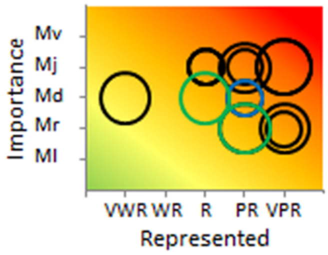
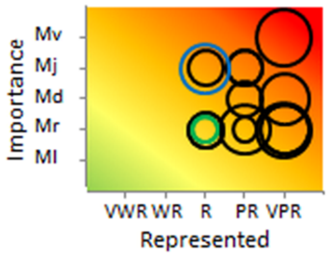
Spawning, periodicity, aggregation and location of spawning areas		Major
Group dynamics, skipped- spawning, density dependence		Major
Impacts of regulations and its effect on the species' apparent global distribution.		Major

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) Natural mortality: 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 1

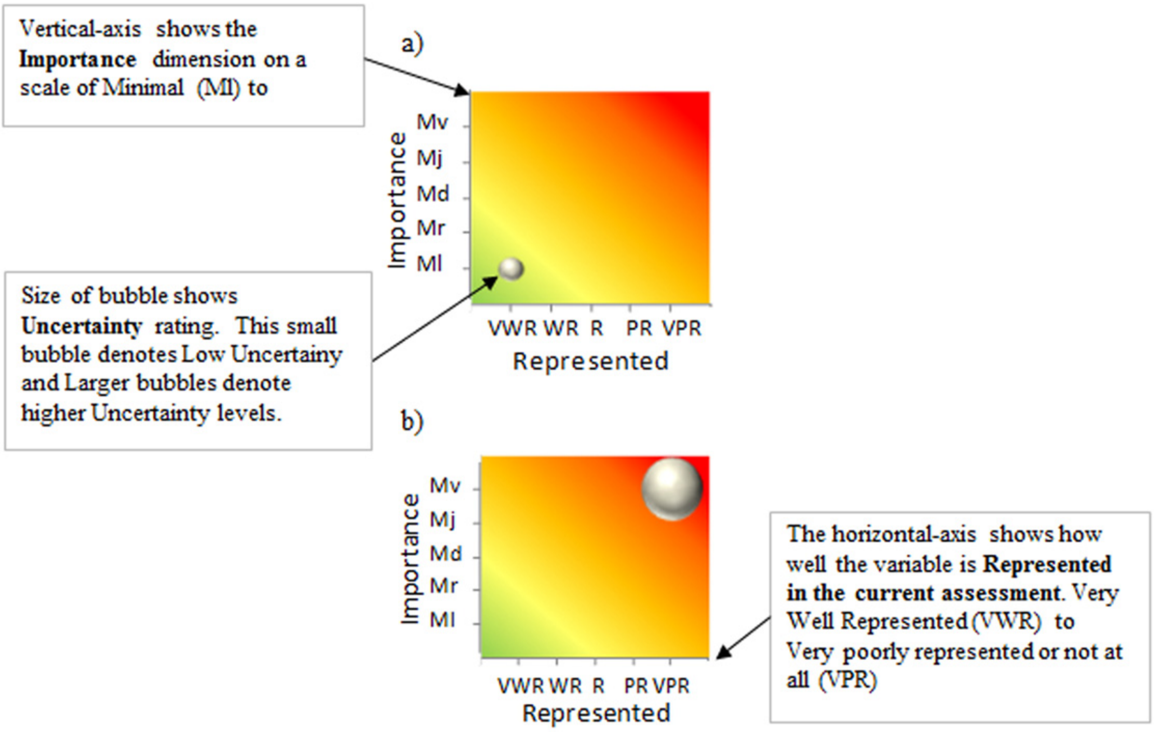

Vertical-axis shows the **Importance** dimension on a scale of Minimal (Ml) to
a)
Mv
Mj
Md
Mr
Ml
Importance
VWR WR R PR VPR
Represented
Size of bubble shows **Uncertainty** rating. This small bubble denotes Low Uncertainy and Larger bubbles denote higher Uncertainty levels.
b)
Mv
Mj
Md
Mr
Ml
Importance
VWR WR R PR VPR
Represented
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

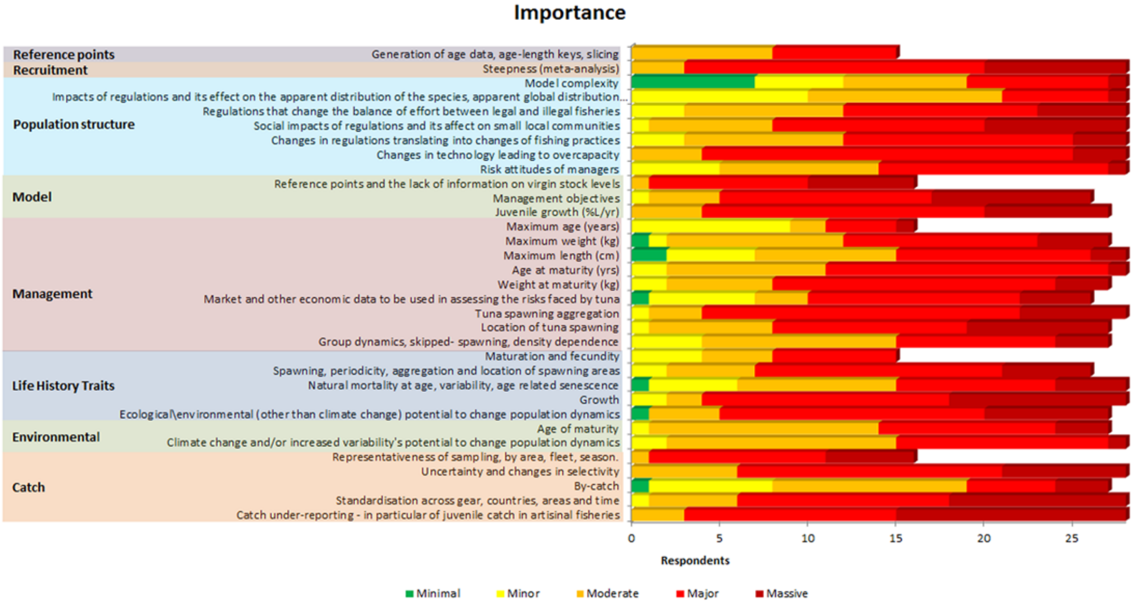
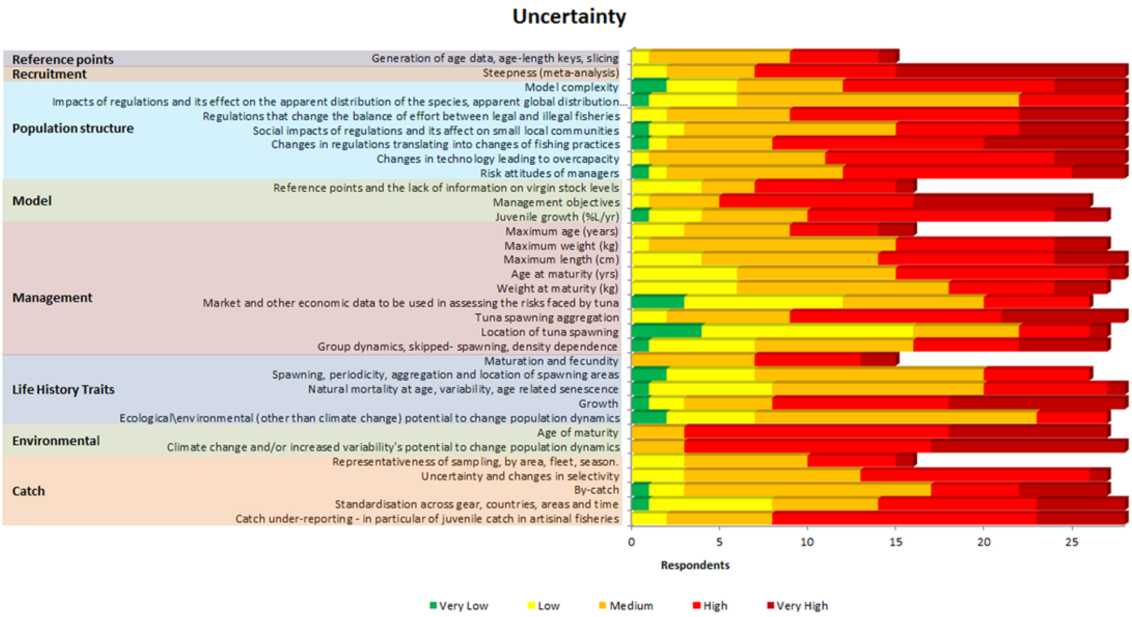

Importance
Reference points
Generation of age data, age-length keys, slicing
Recruitment
Steepness (meta-analysis)
Population structure
Model complexity
Impacts of regulations and its effect on the apparent distribution of the species, apparent global distribution...
Regulations that change the balance of effort between legal and illegal fisheries
Social impacts of regulations and its affect on small local communities
Changes in regulations translating into changes of fishing practices
Changes in technology leading to overcapacity
Risk attitudes of managers
Model
Reference points and the lack of information on virgin stock levels
Management objectives
Juvenile growth (%L/yr)
Management
Maximum age (years)
Maximum weight (kg)
Maximum length (cm)
Age at maturity (yrs)
Weight at maturity (kg)
Market and other economic data to be used in assessing the risks faced by tuna
Tuna spawning aggregation
Location of tuna spawning
Group dynamics, skipped- spawning, density dependence
Life History Traits
Maturation and fecundity
Spawning, periodicity, aggregation and location of spawning areas
Natural mortality at age, variability, age related senescence
Growth
Ecological\environmental (other than climate change) potential to change population dynamics
Environmental
Age of maturity
Climate change and/or increased variability's potential to change population dynamics
Catch
Representativeness of sampling, by area, fleet, season.
Uncertainty and changes in selectivity
By-catch
Standardisation across gear, countries, areas and time
Catch under-reporting - in particular of juvenile catch in artisinal fisheries
0
5
10
15
20
25
Respondents
Minimal
Minor
Moderate
Major
Massive

Figure 3


Uncertainty
Reference points
Generation of age data, age-length keys, slicing
Recruitment
Steepness (meta-analysis)
Population structure
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Impacts of regulations and its effect on the apparent distribution of the species, apparent global distribution...
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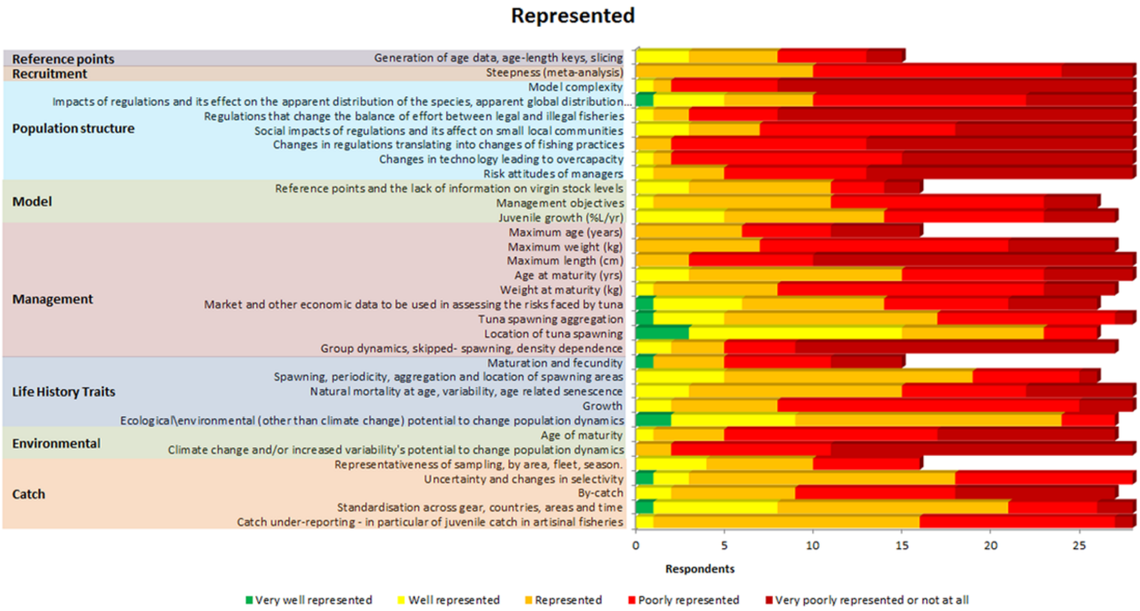
Catch
Representativeness of sampling, by area, fleet, season.
Uncertainty and changes in selectivity
By-catch
Standardisation across gear, countries, areas and time
Catch under-reporting - in particular of juvenile catch in artisinal fisheries
0
5
10
15
20
25
Respondents
Very Low
Low
Medium
High
Very High

Figure 4



Represented
Reference points
Recruitment
Population structure
Model
Management
Life History Traits
Environmental
Catch
Generation of age data, age-length keys, slicing
Steepness (meta-analysis)
Model complexity
Impacts of regulations and its effect on the apparent distribution of the species, apparent global distribution...
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Representativeness of sampling, by area, fleet, season.
Uncertainty and changes in selectivity
By-catch
Standardisation across gear, countries, areas and time
Catch under-reporting - in particular of juvenile catch in artisinal fisheries
0
5
10
15
20
25
Respondents
Very well represented
Well represented
Represented
Poorly represented
Very poorly represented or not at all

Figure 5.

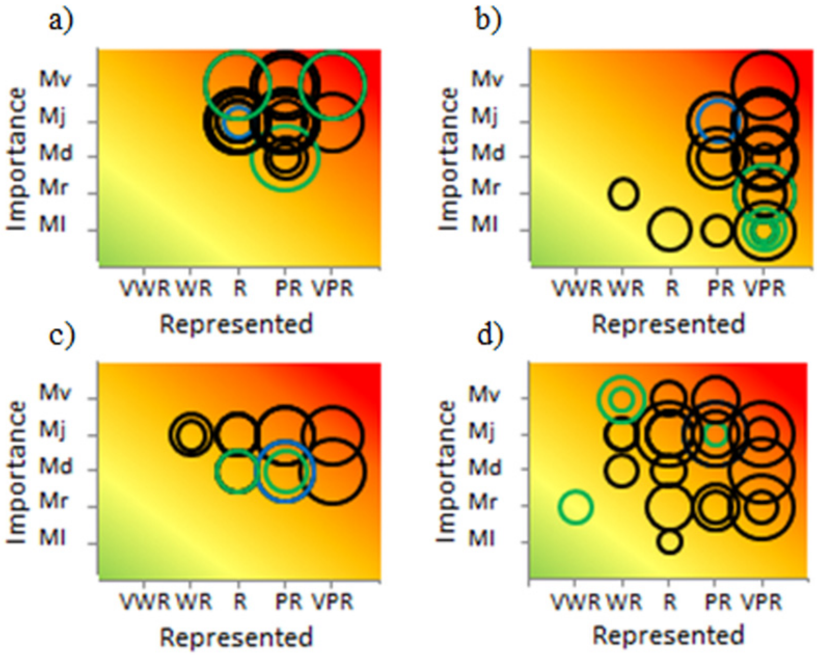
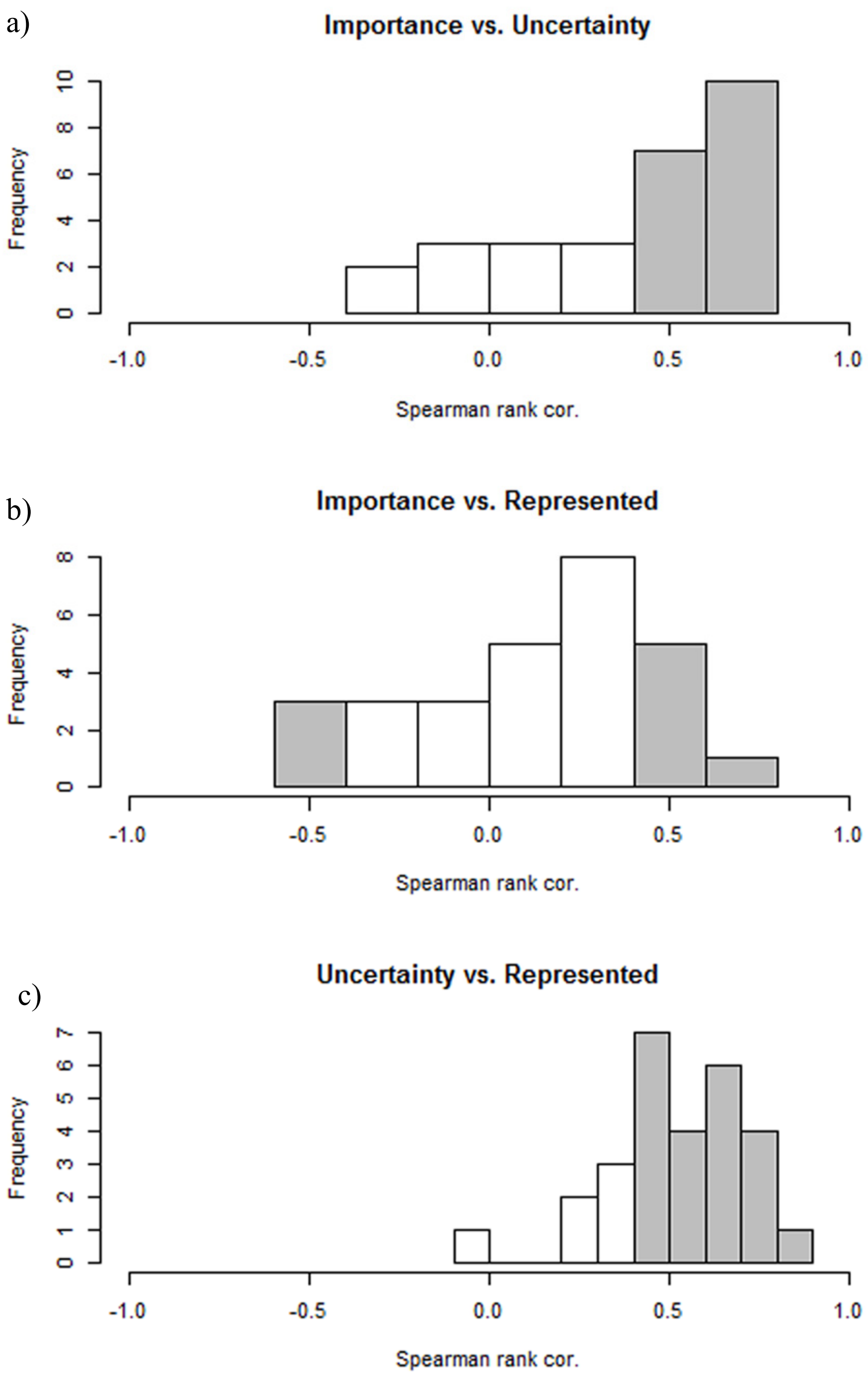


Figure 6


a)
Importance vs. Uncertainty
Frequency
Spearman rank cor.
b)
Importance vs. Represented
Frequency
Spearman rank cor.
c)
Uncertainty vs. Represented
Frequency
Spearman rank cor.