Availability: 7 October 2015
IOTC-2015-WPM06-INF07

Kell, L., Levontin, P., D. C., Harley, S., Kolody, D., Maunder, M., Mosqueira, I., Pilling, G., and Sharma, R. (2015). Fisheries management science: an introduction to simulation based methods. In Edwards, C. and Dankel, D., editors, *Fisheries management science: an introduction to simulation based methods.*

Contents

1 Introduction

Tuna Regional Fisheries Management Organisations (tRFMOs) are intergovernmental organisations that are charged with data collection, scientific monitoring and the management of tuna and tuna-like species. There are five tRFMOs, namely the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC) and Western and Central Pacific Fisheries Commission (WCPFC). As institutions they are still evolving, as some have been created only recently (i.e. WCPFC) while others are older, dating back to the 1940s (i.e. IATTC). The commissions are political bodies responsible for making management decisions, which are subsequently adopted by member states. Advice is provided by Scientific Committees, in some cases stock assessments are performed by working groups comprising representatives from member states (e.g. CCSBT, ICCAT and IOTC), while in the others work is either performed in house (IATTC) or contracted out (WCFPC).

As a major step towards harmonisation the tRFMOs have recently agreed on a common management advice framework, known as the Kobe Framework (Anon, 2009); an agreement to adopt a common methodology for sharing scientific resources, to facilitate data sharing, and to coordinate management, compliance and enforcement approaches. The framework also provides a basis for cooperation on improving how uncertainty is quantified, incorporated into analyses and communicated. A particular emphasis is therefore devoted to risk defined as in Chapter 2 - a chance event with negative consequences. Although there are several actual definitions of risk, most standards define risk as *an uncertainty that, if it occurs, will have an effect on achieving objectives* (Hillson, 2011). The quantification of risk requires estimating the probability of an event occurring and the severity of any consequences.

A discussion of risk needs to begin with an understanding of management objectives. In fisheries objectives are represented by target reference points (TRPs), which are used with limit reference point (LRPs) that indicate the state of a fishery or a stock considered undesirable and which should be avoided with high probability. It is preferable that risk tolerance is made explicit, for instance, stipulating that there should be no more than a 5% chance of breaching a LRP. Reference points can be used as part of a harvest control rule (HCR); an management decision algorithm which specifies in advance what actions need to be taken and when, in order to over time maximise the probability of achieving targets and minimise the risk of breaching limits.

The main management objective when the tRFMOs were established was to achieve the maximum sustainable yield (MSY). This requires maintaining total and adult stock biomass at the levels associated with MSY (i.e. B_{MSY} and SBB_{MSY}) and fishing mortality at a level that would on average achieve MSY (F_{MSY}). Therefore management was based on biomass and fishing mortality TRPs linked to MSY. Subsequently the United Nations Conference On Straddling and Highly Migratory Fish Stocks (United Nations, 1995) redefined F_{MSY} as a least stringent standard for a LRP; i.e. this implies that now the probability of exceeding (F_{MSY}) must be lower than 50%.

Due to the higher expectations for sustainability of contemporary management agreements (see Brown et al., 1987; Harley et al., 2012), and in order to bring themselves in line with the world mandate for adopting the precautionary approach, tRFMOs are now starting to incorporate reference points (LRPs and TRPs) into advice and evaluating their performance as part of HCR using Management Strategy Evaluation (MSE). MSE provides a formal way to test the robustness of reference points to some of the known sources of uncertainty. When running an MSE control actions from the HCR are fed back into an Operating Model (OM) that represents the system being managed so that its actions on the simulated stock and hence on future fisheries data is propagated through the stock and fishery dynamics. MSE may be used to simulation test a Management Procedure (MP), which is the combination of pre-defined data, together with an algorithm to which such data are input to provide a value for a TAC or effort control measure. The MP may include a HCR and a stock assessment estimator, but does not have to for example CCSBT provides a model free example of a MP that is based on year to year changes and trends in empirical indicators.

Management Strategy Evaluation can be a part of the Kobe Framework by helping to quantify uncertainties associated with different levels of exploitation or different approaches to adaptive management. When designing elements of a management system using MSE a key benefit is greater conformity to the precautionary principle of resource exploitation, since performance is judged under conditions of (simulated) incomplete knowledge. The degree of this benefit depends on the effort made to elicit and represent important uncertainties within the simulations. The Kobe Framework is not necessarily going to supersede the current institutional arrangements of each Commission when negotiating decisions. However, it may assist in making management measures more robust, i.e. ensure that the management objectives are met with high probability despite the presence of uncertainty or stressful environmental conditions (Radatz et al., 1990).

Execution of a MSE can be summarised in the following steps (i.e. described in greater detail by Punt and Donovan, 2007)

1. Identification of management objectives and mapping these into statistical indicators of performance or utility functions;
2. Selection of hypotheses for considering in the OM that represents the simulated versions of reality;
3. Conditioning of the OM based on data and knowledge, and weighting of model hypothesesdepending on their plausibility;
4. Identifying candidate management strategies and coding these as MPs;
5. Projecting the OM forward in time using the MPs as a feedback control in order to simulate the long-term impact of management (Ramaprasad, 1983); and
6. Identifying the MP that robustly meet management objectives.

Performance of a simulated MP is measured in terms of risk, based on probabilistic measures of the simulated frequencies with which management objectives are met. Statistics from the OM might also be collected to assess additional subjective (according to elicited stakeholder views) consequences, for instance modelled impacts on employment, profits or ecosystem. The involvement of stakeholders is a key point; it is increasingly a normative view within fisheries management that stakeholders should be the foundation of the decision making process. In order to ensure that stakeholder concerns are included it is essential to communicate to stakeholders how uncertainty is quantified, to solicit their feedback from the very beginning in specifying hypothesis and representing uncertainties within the OM, and respond where possible with amendments to the simulation framework.

The MSE approach is flexible and not restricted to the goals of finding an MP that will run on autopilot (as described in Hillary et al., Chapter 8 this volume); since MSE can be an exploratory tool employed to examine the sensitivity of the system to various beliefs about how it functions (e.g. Kell and Fromentin, 2007). Case-specific MSEs can facilitated decision making-process within tRFMOs by improving the understanding of risks and reconciling the differences of opinions among stakeholders regarding the implications of outstanding gaps in knowledge.

We first review the application of the Kobe Framework and the development of LRPs and MPs by the tRFMOs. We then discuss how the Kobe Framework can be extended to utilise more fully approaches for identifying, quantifying and communicating risks - in particular, the potential for MSE to make the Kobe Framework more robust and more inclusive.

2 Scientific Advice Framework

In traditional stock assessment and management based upon it is assumed that the system dynamics are known and expressed in the form of a mathematical model and that a management control (e.g. TAC) can be adjusted based on that knowledge. In engineering this is known as open loop feed-forward control (Velthuis, 2000). Pure feed-forward control is also termed 'ballistic', since once a control has been set it cannot be adjusted (Whitbeck and Wolkovitch, 1982). Corrective adjustment must be done by updating the formal stock assessment on a regular basis and the Commission agreeing new management measures. An alternative is a closed-loop control systems, termed 'cruise control,' which automatically adjusts a control in response to feedback from the system. Feedback relaxes the requirement of having to have an exact model of the system being managed since the effect of the controls action on the system are monitored and adjusted accordingly, e.g. as in the case of the southern bluefin MP where TACs are set based on trends in indices of abundance (see chapter 8). MSE is a simulation of closed-loop feedback systems. MSE is widely thought of as a process that is used to create a MP that runs for several years on autopilot, without the need for managers to agree on measures based on an annually updated stock assessment. However, MSE can also be used for strategic proposes to explore robustness of existing or proposed elements of a management regime.

When managing fisheries, decisions have to be made under incomplete knowledge in a stochastic environment. Therefore the Precautionary Approach (PA, Garcia, 1996) requires that undesirable outcomes should be anticipated and measures taken to reduce the probability of them occurring and/or the magnitude of their impact. This requires managing the identified causes of uncertainty in order to ensure that management objectives are met, as well as managing the consequences. As such the PA represents a shift towards Risk Management (see chapter 2).

The voluntary Code of Conduct on Responsible Fishing (FAO, 1995) and the United Nations Fish Stocks Agreement (United Nations, 1995) provide the formal basis for the application of the PA to fisheries management. The Conventions of some tuna Regional Fisheries Management Organisations such as the WCPFC and IATTC refer to these codes directly, whilst others do not explicitly address the PA (De Bruyn et al., 2012) as their conventions were signed before the PA was drafted. Yet all five tRFMOs have agreed to take steps through the Kobe Framework process (Anon, 2009), towards a common approach to risk-based management, and hence are moving synchronously towards meeting the needs of the PA.

One of the requirements of the PA is that stocks are assessed regularly with respect to LRPs and TRPs. Given the political complexity of tRFMOs, which include many international partners and stakeholders that deal with a valuable resource about which knowledge is both insufficient and contested, it is unlikely that a system of decision making that relies on negotiations will be replaced by HCRs run on autopilot. Of the five tRFMOs only CCSBT, which manages a single stock with a limited number of member states, has fully adopted a MP approach. In the other RFMOs a simplified robust decision making process might be developed based on the current stock assessment processes to provide guidance, comparison and risk-based advice.

The main outcome of the Kobe Framework is the standardisation of the presentation of stock assessment and management advice relative to reference points. The reference points currently used by the tRFMOs (Anonymous, 2015) are summarised in table 1. Management objectives are mainly articulated through MSY-based target reference points, the values of which depend on the productivity of the stock plus the selectivity of the fisheries and their relative effort. Some tRFMOs also derived LRPs from MSY (e.g. ICCAT and IOTC). WCPFC have used $SSB_{F=0}$ (the spawning stock biomass in the absence of fishing derived from a stock assessment) this has an advantage of not depending on the selection pattern of the fleets. Deterministic estimates of F_{MSY} and B_{MSY} may be derived from the parameters of a stock assessment model. In a stochastic framework, MSY-based reference points are usually obtained by simulation. For example, MSY can be calculated as the largest average long term yield from application of a constant fishing mortality (F, i.e. (F_{MSY}) or from a harvest control rule where F varies as a function of stock size. B_{MSY} is then the average biomass that results from fishing at F_{MSY}, where B_{MSY} commonly refers to the spawning stock biomass. In this case how productivity and fishery selectivity varies over time becomes important.

It is an intention of some of the tRFMOs to test reference points within an MSE setting to determine their potential sensitivity to various sources of uncertainty and their ability to achieve management objectives. One possible outcome of MSE is that these reference points might be revised to reflect a better understanding of the risks arising from the scientific, managerial and other sources of uncertainty.

2.1 Uncertainty

Characterisation of uncertainty is a requirement of the Precautionary Approach, but it is a process that can vary widely in scope depending on how representative it is about involving stakeholders. Traditional stock assessment, and advice based upon it, mainly considers measurement and process error despite research showing that uncertainty about the actual dynamics (structural uncertainty) has a larger impact on achieving management objectives (Punt, 2008). Discussions of uncertainty in the context of stock assessment include limitations in our knowledge of system dynamics, the unpredictability of environmental events and their impacts, the lack of precision in our ability to implement management measures and to monitor stocks and fisheries (Kirkwood and Smith, 1995; Leach et al., 2014). Uncertainties in this system are usually classified in the following manner (after Rosenberg and Restrepo, 1994):

Process error due to the underlying stochasticity in population dynamics such as random variability in recruitment or year-to-year changes in distribution;

Observation error due to sampling and measurement of quantities such as the catch or average size at age;

Model error related to the ability of the model structure to capture system dynamics; including

- **structural uncertainty** due to inadequate models, incomplete or competing conceptual frameworks, or where significant processes or relationships are wrongly specified or not considered. Such situations tend to be underestimated by experts (Morgan and Henrion, 1990) and

- **value uncertainty** model parameters that are treated as fixed inputs because they are difficult to estimate reliably (e.g. stock recruit relationships);

Estimation error arising when estimating parameters of the models used in the assessment procedure; estimation error can result from any of the above uncertainties, or from limitations of the numerical procedures, and is the inaccuracy and imprecision in the estimated model parameters such as stock abundance or fishing mortality rate;

Implementation error where the effects of management actions may differ from those intended, e.g. the inability to achieve a target harvest strategy exactly.

The definitions of Rosenberg and Restrepo (1994) focus on aspects that can be quantified in mathematical models. Particularly as stock assessment working groups often focus on technical aspects related to modelling, such as eliciting prior distributions in Bayesian modelling frameworks or ranges for parameter values. The characterisation of uncertainty is ultimately a pragmatic choice depending on the purpose of a particular application. There are other classifications of uncertainty, for example chapter 2, defines 'statistical uncertainty' which includes the structural, process and observation uncertainties, and combines ‘model error’, ‘ structural uncertainty’ and ‘value uncertainty’ into ‘structural uncertainty’; then summarises the different sources based on those that can be reduced and those that are inherent to the system i.e.

Irreducible aleatoric

- Process
- Implementation

Reducible epistemic

- Statistical
- Structural

Linguistic sources of uncertainty which play a role in communication and elicitation, or uncertainty related to risk perception or vagueness and the possibly contradictory nature of management goals are also important(Regan et al., 2002). The national discourses about resource use, power dynamics among nations based on cultural, economic, and epistemic histories shape the way the problems of internationally shared resources are understood but these crucial differences are rarely articulated in the language of stock assessments. Uncertainties related to institutional and social norms are also important because they pertain to the very definition of a management problem which is a social construct first and foremost.

The transformation of a management mandate into a modelling problem is often been seen as an unproblematic ‘natural’ process determined by the available methodology. But with the proliferation of available modelling alternatives (from single species to ecosystem modelling) it is increasingly evident that uncertainty pertaining to methodology can be pivotal. The scientific advice produced can be radically different depending on the model used. Unless the process of building models is participatory, the modellers have potentially unwarranted control over the means of producing knowledge which influences management decisions. This is why there is an increasing consensus on a definition of risk that covers all known uncertainties, rather than individual elements of it.

Partly for these reasons MSE is increasingly being used to address uncertainties and their effect on management advice. Although MSE can not address every kind of uncertainty, it can accommodate more sources of uncertainties than stock assessment alone. For example MSE can indicate how improving management through Monitoring Control and Surveillance (MCS) or knowledge through focused scientific data collection and research can ensure that management objectives are met (Fromentin et al., 2014). A strength of MSE is that by agreeing management objectives in advance stability can be added to the management decision process. Particularly as MSE requires a dialogue between scientists, managers and stakeholders on how to evaluate alternative management procedures given uncertainty over what time period, which reference points to use, what are the acceptable levels of risks, and what are the possible trade-offs between social and economic objectives, etc (e.g. Röckmann et al., 2012). MSE can lend logical support to a conversation through which outstanding disagreements can be potentially resolved.

2.2 Assessment Frameworks

Assessment advice within the tRFMOs is increasingly being based on integrated models, i.e. IATTC uses Stock Synthesis (SS Methot and Wetzel, 2013), WCFPC Multifan-CL (Hampton and Fournier, 2001) and IOTC uses SS alongside a variety of other models. While ICCAT uses integrated models and virtual population analysis (VPA) most advice is based on biomass dynamic models. Management by CCSBT is based not on stock assessment but a Management Procedure (MP) developed using an integrated age-based OM (Hillary et al., Chapter 8 this volume).

Two main visualisation tools are used as part of the Kobe Framework to present stock assessment advice, namely the Kobe II phase plot (K2PP) and the Kobe II Strategy Matrix (K2SM). The K2PP presents stock status against fishing mortality relative to TRPs as a two-dimensional phase plot. The K2SM lays out the probability of meeting management objectives under different options, including if necessary ending overfishing or rebuilding overfished stocks. Presenting advice in the K2SM format is intended to facilitate the application of the PA by providing Commissions with a basis to evaluate and adopt management options at various levels of risk (Anon, 2009). This enables Commissioners to make management recommendations while taking some sources of uncertainty into account. As an exception the CCSBT does not use the K2SM, since they prefer to consider other performance measures (related to catch levels and catch variability) as well as stock status.

The K2PP identifies quadrants (regions) where the stock is overfished (biomass or SSB is less than B_{MSY}) or overfishing is occurring ($F \geq F_{MSY}$) and a target region (where both SSB $\geq SSB_{MSY}$ and $F \leq F_{MSY}$). In the case of biomass dynamic stock assessment model results biomass may be used instead of SSB. The target region is also called the *"green"* quadrant, referring to the colour scheme typically used when presenting the K2PP. The plots can be used to indicate for example when management plans to recover the stock to the target region should be implemented. In practice there is a lot of diversity in how status is presented in the K2PPs and a range of examples are shown in Figure 2; these are not exhaustive as many variants are used both between and within the tRMFOs.

In some cases results from a single model that was run with different fixed values are presented, as is the case with the IATTC example for the Eastern Pacific bigeye SS assessment (Aires-da Silva and Maunder, 2012) presented in Figure 2a. The 26 scenarios represent uncertainty about the values of parameters used in the assessment, i.e. steepness, M and the average length of the oldest individuals, that are fixed structual assumptions in the models. The base case is in the target quadrant (i.e. the lower right quadrant). There is a curvilinear relationship between F/F_{MSY} and SSB/B_{MSY}. Reducing steepness results in the stock becoming overfished (i.e. SSB/B_{MSY} decreases) and overfishing occurring (i.e. F/F_{MSY} increases). While changing M and the length of the oldest individuals results in a decrease/increase in F/F_{MSY} and an increase/decrease in SSB/B_{MSY}. In the IATTC reference points vary by year; B_{MSY} changes as historic recruitment varies and F_{MSY} as selectivity and the mix of gears changes.

The Indian Ocean Tuna Commission adopts a similar approach to IATTC, presenting a range of assessment results based on model assumptions, the Stock

Synthesis assessment for Indian Ocean albacore is presented in Figure 2c; this time 36 scenarios were evaluated for different values of natural mortality (M) and steepness, assumptions about effort creep and weighting of data. In this example the results were contoured to generate a probability density. The WCPFC also explores value and structural uncertainty, using SS based on an uncertainty grid, where individual combinations of alternative parameter values are run as separate assessments. For the silky shark assessment, Figure 2d, alternative stock assessment runs (2,592 scenarios based on steepness, growth, M, etc.). The size of the circles correspond to plausibility based on expert judgement.

The K2PPs can also be used to display parameter uncertainty, as well as point estimates, as is the case in the ICCAT example (Figure 2b). Rather than using integrated stock assessment models and varying parameter values or assumptions, ICCAT generally uses simpler stock assessment models and varies the data used for fitting. For example, the South Atlantic albacore assessment was performed using two different software packages that implement biomass dynamic models; namely ASPIC using maximum likelihood (Prager et al., 1996) and bootstrapping and BSP using Bayesian simulation (McAllister and Babcock, 2003). For each package there were two model specifications (logistic and Fox production functions) and two catch per unit effort (CPUE) series used as proxies for stock biomass. The large circles, in the ICCAT plot, denote the medians from each assessment run and the small dots individual estimates from Monte Carlo simulations; marginal probability distributions are also shown along the x and y-axis. The point estimates are all different and the Bayesian estimates are much wider than those obtained by bootstrapping.

The main form of uncertainty presented in the K2PPs above was model error due to value uncertainty: for the IATTC and IOTC the same stock assessment modelling framework is used for a limited number of scenarios by varying a single value at a time, whereas the WCFPC used a structural uncertainty grid where all values are varied at the same time. Only in the ICCAT example were uncertainties about the point estimates shown, although other tRFMOs present similar plots. In this case the procedure used to estimate the variance around the point estimates (by either bootstrapping or using Bayesian simulation) give different perceptions of risk (Magnusson et al., 2012). Which in turn changing the probabilities provided by scientists for management advice. Managers are often unaware of these issues, while the uncertainty which concern stock assessment scientists is mainly related to their own personal modelling choices, rather than providing advice related to the management of risk. But this aspect is commonly lost in the process of communicating stock assessment results to decision makers. Thus, even when some sources of uncertainty were present or accounted for at some stage of the assessment process; this information might not filter through to the stakeholders.

2.3 Management

Once the assessment of current stock status is accepted the next step is to advise on the measures required to achieve management objectives. The K2SM is intended to be a standardised format for presenting advice on measures required to achieve a management target with a certain probability within a given time scale (Anon, 2009). For example ICCAT (RES 11-14) requires the Standing Committee for Research and Statistics (SCRS) to provide three Kobe II strategy matrices indicating for different total allowable catches (TACs) the probabilities by year of $B \geq B_{MSY}$, $F \leq F_{MSY}$ and $B \geq B_{MSY}$ and $F \leq F_{MSY}$. An example based on the 2012 ICCAT East Atlantic and Mediterranean bluefin assessment is presented in Table 2. The objective is to recover the stock to the target (i.e. bottom right) quadrant of the K2PP. IOTC uses a different format for the K2SM that provides a summary of measures that meet management objectives, e.g. Table 3 which uses the same data as in the previous Table. This shows the probability of ending overfishing and recovering the stock for different catch levels.

The K2SM presented differs from decision tables, the latter provide performance measures for a set of alternative management actions under different states of nature (Punt and Hilborn, 1997; Maunder and Aires-da Silva, 2012). Table 6 shows an example from IATTC for yellowfin tuna in the Eastern Pacific. Assessment scenarios considered were two assumptions for the steepness of the stock-recruitment relationship and two levels of recruitment variability (Minte-Vera et al., 2013). The Table shows the fraction of the current fishing mortality (δ) required to ensure that fishing mortality is below the target (F_{MSY}) and limit ($1.4F_{MSY}$) with a given probability.

The probabilities presented in the bluefin example above were averages derived from different historic assessment and projection scenarios (i.e. uncertainty about historic catch levels, future recruitment and selection pattern) where all were given equal weight. Table 4 shows the probabilities of achieving management objectives for each source of uncertainty. A difference between Tables 3 and 4 is that in the latter the effect on management objectives of the different sources of uncertainty are shown. This is consistent with the definition of risk based management that requires identifying the consequences of uncertainty in order to manage the impact on management objectives. Mantyniemi et al. (2009) showed there was an economic benefit of resolving uncertainty about the stock recruitment relationship. If the productivity of the stock is underestimated then yield will be forgone, while if it is overestimated the stock may be overfished. Table 3, by averaging over different future recruitment levels the consequences of resolving uncertainty about recruitment is masked while in Table 4 the consequences of different recruitment regimes is identified.

3 MSE

The summaries of the application of the Kobe framework above is based on traditional stock assessment. However, MSE is increasingly being used to evaluate the robustness of advice frameworks to the main sources of uncertainty. There is an important difference between conducting an MSE to develop an MP based on optimisation of objectives that will be run on autopilot and comparing alternative assessment and management options, e.g. for choosing reference points. In the later case MSE is used to inform management, not to dictate it. The CCSBT has developed an Management Procedure (MP) using MSE but to date no other tRFMO has implemented MPs based on MSE, while ICCAT for example has used MSE to evaluate the implicit MP of ICCAT (Kell et al., 2003) to develop LRPs. An implicit MP is a set of rules for management of a resource that contains all the elements of an MP but is not run on autopilot (Kell et al., 2005a). According to Rademeyer et al. (2007) an implicit MP is also an MP that has not been simulation tested.

3.1 Examples

The CCSBT chose to develop an MP using MSE because they had two plausible assessments that gave contradictory estimates of stock status and productivity, and as a result a TAC could never be agreed. The CCSBT does not have MSY as an objective reflecting the time that the convention was signed (1994) and the improved understanding of why MSY is not very helpful as a specific technical objective (Holt, 2011). The CCSBT does not use the K2SM, but do use the K2PP as part of the agreed reporting to FAO and other tRFMOs, but is thought of more as a tool for objective elicitation in the context of what is agreed in conventions and the UN Fish Stocks Agreement (United Nations, 1995). When using MSE to develop an MP, performance statistics based as catch, catch variability, CPUE and biomass/recruitment are used, as these ensure that results actually mean something to stakeholders.

A reason for adopting MSE by the CCSBT was to help resolve scientific disputes and embrace uncertainty by developing an OM which included plausible alternative hypotheses about stock and fishery dynamics. This in turn allows the selection of a robust management procedure that meets the CCSBT objectives. To do this the CCSBT used a grid of quantitative uncertainties when designing the OM (Table 5). The grid specified values for key parameters where there was little information in the data. This allowed quantitative evaluation of the impact of uncertainty on management objectives. Priors or resampling based on the objective function was also possible (see Table 5). During OM development a *Reference Set* was used in a series of *Robustness trials* in order to tune the MP. Subsequently the OM scenarios were refined to narrow uncertainty in order to focus on things that really made a difference to performance measures and management objectives. The main objective was to rebuild the stock by 2035 with a 70% probability, but trade offs between MPs were also considered. Since if several MPs achieved the rebuilding target there may be other characteristics that made a particular MP more desirable, e.g. the relative risk of catch limit reductions following previous increases in catches.

In the other tRFMOs, although no MP has been evaluated and implemented, the trend is to use stock assessment models as OMs and then test simpler MPs or alternative reference points for use as part of HCRs. For example the IOTC has developed an OM for albacore conditioned using SS and a grid of factors and levels based on the stock assessment. While ICCATs advice, including limit reference points for North Atlantc albacore is now based on a biomass dynamic model which has been evaluated using an OM based on Multifan-CL, which was previously used to provide stock assessment advice (Kell and De Bruyn, 2013). This makes the transition from stock assessment based on integrated models to advice based on simpler assessments or rules possible for stocks that have been assessed using SS (Maunder, 2014).

3.2 Steps

The first step when conducting an MSE is to identify management objectives, the Kobe framework provides a basis for doing this. Since it stipulates that the stock should be in the green quadrant of the phase plot, i.e. it defines a target region based on biomass and F reference points. However, the actual reference points, probabilities and time scales still need to be agreed on a case-specific basis. The kobematrix helps to provide a framework in which probabilities and time scales can be discussed. Also the same biological objectives can be achieved with different social and economic consequences. For example F can be reduced through time and/or area closures or capacity reduction as well as TACs. Therefore managers have to consider trade-offs and long/short term outcomes related to social and economic objectives (ICCAT, 2014). Objectives may include the minimisation of variability in catch and/or effort, as in the case of the CCSBT, since wide annual fluctuations in catch and effort limit the ability of the fishing industry to plan for the future (Kell et al., 2005a,b). In the western Pacific Ocean, the Parties to the Nauru Agreement (PNA) have agreed a range of management objectives for the skipjack purse seine fishery, related to stability of allocation of fishing effort, resource sustainability, economic goals, limiting impacts on the distribution of skipjack and being risk adverse. There is an overall objective for no increases in catch, maintaining current levels of effort, and limiting impact on other species (McKechnie et al., 2013).

Although MSY may be an important policy goal it is not necessarily a useful technical objective. In an MSE performance measures are based on quantities from the OM, and reference points based upon a model estimate such as F_{MSY} or B_{MSY} do not need to be used in a MP (or HCR) as long as management objectives related to yield are meet. The CCSBT provides a model free example of a MP that is based on year to year changes and trends in empirical indicators (i.e. CPUE and fisheries independent indices); reference levels are then tuned to meet management objectives using MSE. Where tuning refers to adjusting the parameters of the MP to try and achieve the stated objectives represented by the OM. Model based MPs, e.g. those based on a stock assessment model, may include the estimation of MSY based reference points, but the values of F, F_{MSY}, B and B_{MSY} from the OM do not need to be equivalent to their proxies in the MP. For example if a stock assessment models used in the MP is structually different from that used to condition the OM.

The choice of OM scenarios is crucial since the MP (or HCR) is tuned to the OM, therefore the best MP is a function of the OM scenarios chosen. Any bias in the OM scenarios will lead to bias in the performance of the MP. A MSE does not have to be based on a complex OM since a relatively simple OM may provide an evaluation of what MPs are likely to perform well (Carruthers et al., prep). However, to evaluate robustness the choice of scenarios is important, since if an assumption is not modelled in the OM, e.g. about stationarity (e.g. Szuwalski et al., 2014) or population structure (e.g. Kell et al., 2009) then it will be difficult to say much about its impact on achieving management objectives.

There are many ways of constructing OMs (Kell et al., 2006). It is common to use the current stock assessment model as the OM, but alternatively a more flexible model that can represent all available data may be especially constructed for the MSE. However not all relevant data sets may be available and so priors may be required for difficult to estimate parameters and to reflect expert opinion. The use of a stock assessment model implies that the assessment model describes nature as well as possible in a model. However, if a MP cannot perform well for simpler models, it is unlikely to perform adequately for more realistic representations of uncertainty. To test the robustness to alternative hypothesis about the dynamics of the system, e.g. driven by climate and environmental uncertainty, will require hypotheses about how biological parameters may change in the future (Punt et al., 2013) rather than relying on models fitted to historical data sets. Such hypothesis can be weighted in terms of their plausibility qualitatively based on expert opinion. The International Whaling Commission (IWC) also provides an example of combining qualitative judgement of OMs scenarios (high, medium and low likelihood) within MSE (Punt and Donovan, 2007).

Examples based on tRFMOs experiences illustrate the inherent flexibility of MSE methodology, the wide range of situations where it has been applied, as well as the potential for these applications to deepen and expand in the future to better suit the needs of stakeholders within the risk-based management paradigm.

4 Communicating and Assessing Risk

As discussed above the management of risk requires the identification of management objectives and an assessment of how uncertainty affects the chances of achieving those objectives. In MSE, once the management objectives are mapped to performance measures, OMs are designed to reflect the main uncertainties about the system. Punt et al. (2014) recommended that when conducting an MSE, the range of uncertainties considered should be sufficiently broad so that new information collected after the management strategy is implemented would generally reduce rather than increase the initial range. A major impact on the risk assessment is how to select, reject and weight alternative OM hypotheses. When specifying external weights or priors in a Bayesian approach (unless non-informative priors are used) expert judgement needs to be applied and consensus amongst experts should be sought. However, agreeing OM hypotheses and associated weights is potentially problematic. There is a need to avoid weighting choices being influenced by management implications. Therefore, ideally, weights for scenarios should be pre-agreed through informed discussion before any computations are undertaken and results presented. However, after identifying hypotheses that although plausible make little difference in terms of management, it might be acceptable not to consider them further (ACE, 2007).

The Atlantic bluefin risk assessment serves as an example of an attempt to formally include stakeholders when conducting an MSE. First Fromentin et al. (2014) reviewed the historic treatment of uncertainty in the assessment and then Leach et al. (2014) used a risk-based approach with stakeholders to identify and prioritise uncertainties for inclusion in the OM (Figure 4). Then Levontin et al. (2014) discuss how to turn a qualitative elicitation exercise into a quantitative procedure for use in MSE.

Leach et al. (2014) describe the elicitation methodology used to compile a prioritised list of uncertainties. Three dimensions of uncertainty were elicited: Importance, being the potential impact on management goals and Knowledge being the potential to reduce uncertainty through more research (noting that some sources of uncertainty such as natural variability may not be reducible, see Chapter 2. A third component related to the extent to which a given source of uncertainty was already accounted for in the assessment process. Among the stakeholders whose views were solicited were managers, scientists and NGOs.

Eliciting and representing uncertainties is a necessary step for MSE to ensure that legitimate concerns of stakeholders are part of the testing process for candidate management procedures. The methodology was intended to allow a qualitative prioritisation of uncertainties, while also visualising the degree of consensus among stakeholders on particular issues. An example of the elicitation exercise is shown in Figure 4, each hoop shows the views of a single assessor (i.e. stakeholder) and the hoop size the degree of epistemic uncertainty associated with a variable (i.e. small hoops = low and large = high uncertainty). Where the variable is for example the assumptions about natural mortality used in the assessment. The vertical axis displays an assessor on beliefs about the importance of that variable (Ml = minimal; Mr = Minor; Md = Moderate; Mj = Major; Mv = Massive) and the horizontal axis shows the degree to which the assessor believes it is included in the current assessment.

Perceptions of uncertainty in fisheries often vary widely among scientists, industry and other interest groups, so such tools that can facilitate inclusion and representation of different opinions are useful when decision-making depends on broad agreement and when effective management depends on commitment from stakeholders. The intention is to repeat this analysis after the MSE process has been carried out to provide a quantified measure of how some uncertainties impact the probability of achieving management objectives and how the views of managers and scientists change. This will give us a measure of acceptance among stakeholders of MSE as a valid way to assess risks.

Figure 3 shows a decision plot based on the IWC approach; the panels represent the MPs, dots the OMs and the bars within a panel the performance measures. For a MP to be acceptable all OMs (dots) must fall in the lower shaded area that represent acceptable performance. Based on this plot only MP4 and MP5 are acceptable. The performance measures are $P(SSB > B_{MSY} > 60\%$, $PF < F_{MSY} > 60\%$, $P(Yield > MSY) > 50\%50$ and AAV in Yield and Effort $< 30\%$. The choice of OM and performance measures is therefore critical and should be agreed prior to presentation of such a plot; to have a basis for choosing an acceptable MP requires prior agreement on the management objectives, and specifically, quantities, targets, probabilities and time scales over which the values related to management objectives are calculated.

5 Discussion

The CCSBT, the only tRFMO to have developed an MP through MSE, does not present advice in the Kobe Advice Framework. This is because MSE requires a more proactive approach to uncertainty. The K2SM, while a useful tool for providing a summary of options, by averaging over all the sources of uncertainty fails to help prioritise research, monitoring and enforcement activities to manage risk. Reformatting the K2SM as a decision table (Table 6) would be a step towards showing the effect of uncertainty and would help in deciding which uncertainties to include in MSE trials. The K2PP and K2SM are blunt instruments because they only depict a narrow range of objectives that are used to define the green area of the K2PP. By contrast, when conducting an MSE a range of graphical summaries are required to allow decision-makers to understand the results from the MSE and depict a wider range of trade-offs (Punt et al., 2014). Choice plots (Figure 3) are another method of visualisation, and when communicating modelling results appropriate tools need to be developed in collaboration with stakeholders.

While a greater range of sources of uncertainty are now commonly considered within MSEs, it is still a process that can be perceived as limited from a stakeholder point of view. Many sources of uncertainty that concern stakeholders may not be possible to include within MSEs in a satisfactory manner. Computational limitations prevent an exploration of all of the interactions among different sources of uncertainty leading potentially to an underestimation of risk. These and related limitations inherent in model-based risk assessment necessitate a need for an empirical validation that the MSE approach to risk assessment is a reliable methodology. Simply put, what is the probability that a MP identified as robust through an MSE will indeed perform safely in the real world? Several MPs have been in place long enough to answer this e.g. New Zealand lobster (Chapter 6) and North Sea Haddock (Chapter 12).

Uncertainty related to communication at every stage of risk management is crucial. Having elicited uncertainties from stakeholders it is necessary to inform them about how a subset of these uncertainties are evaluated within MSE, what are the implications of MSE for risk perceptions and what is the basis for trusting the MSE process in comparison to other risk assessment methods. Without this, engagement with and buy-in for a MP from all stakeholders will be impossible.

Coding a resource allocation problem in mathematical terms does not make an approach 'objective', meaning it does not in itself resolve the conflicting value systems which may be present and of primary interest to stakeholders. Values attached to resources might depend on gender, age, income, ethnicity, nationality, world view, culture and language. Similarly, attitudes to risk might vary among stakeholders, complicating MSE ability to assert that risk acceptability criteria have been met. Yet there is a tendency to see modelling as universalist, unaffected by implicit or explicit agendas or politics. The language of programming MSE is anything but that, if only because of its group exclusivity - in most evaluations only a few of the programers are actually 'fluent' in that language, and the rest of the stakeholders rely on the core group's efforts to communicate results. Many barriers to such communication exists even among the specialists, as it is not uncommon even in a peer-review process to read 'I could not verify the mathematical details, but the authors seem to know what they are doing.' The issue of a lack of trust among stakeholders due to perception that data which supports the modelling is corrupt is well known. Therefore, not just various sources of uncertainties, such as those already mentioned in Chapter 2, but social aspects of values, trust, and communication are important to consider in order for the MSE process to be successfully inclusive.

6 Summary

MSE can be used to develop a MP that runs on auto (e.g. Hillary et al., 2013) or to address strategic questions that inform management decisions (e.g. Kell et al., 2003). One reason for the increased interested in MSE is because LRPs and HCRs are required for certification schemes, e.g. Marine Stewardship Council. Scientific Committees of the tRFMOs have made the logical step that LRP make sense as part of a HCR and the best way to evaluate a HCR is to use MSE.

However, there is no consensus within the tRFMOs about moving to MPs. Although the K2SM is an implicit HCR since once objectives and associated probabilities and time scales are agreed then management options such as a TAC can be read from the K2SM. The K2SM could therefore be simulation tested using MSE (see Kell et al., 2003, 2005a,b).

The first step of MSE is the identification of management objectives, which requires a dialogue between managers and stakeholders. The Kobe framework has helped in this respect as have the Kobe phase plot and matrix. However to fully address the effect on uncertainty on achieving management objectives requires a move towards Risk Management. MSE can help make that step, especially if it helps the tRFMOs to consider social and economic as well as biological objectives.

Scientists have been buried in abstract concepts, mystifying to even the most informed fisheries policy person for far too long, thereby diverging themselves from matters of direct relevance to stakeholders. The approach suggested in this chapter would help improve the dialogue at all levels.

6.1 Acknowledgements

This work was conducted under the Terms of Reference of the Tuna RFMO MSE Working Group.

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8 Tables

9 Tables

10 Figures

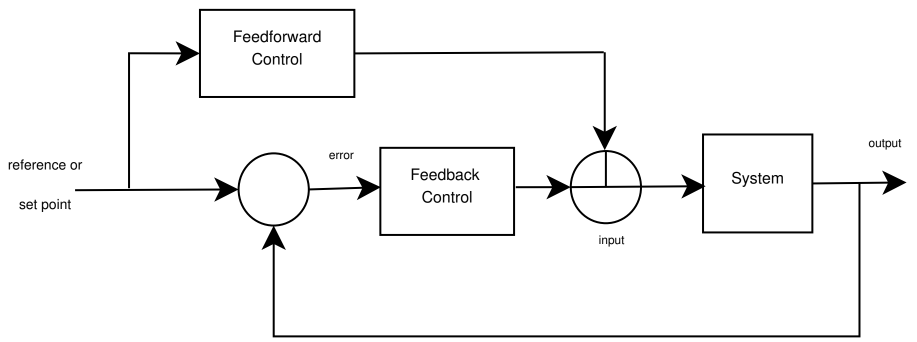


Figure 1: A comparison between feed forward and feedback control systems. The top control shows a feed forward control system ideally based on an exact model of the system; the bottom control is based on feedback which is reactive and automatically compensates for disturbances (i.e. errors) and in practice can be very simple if the signal used to monitor the system is adequate.

11 Glossary

Table 1: Summary of reference points used by Tuna RFMOs.

	CCSBT	IATTC	ICCAT	IOTC	WCPFC
Limits	None	For tropical tunas: $F_{0.5R0}$ and $B_{0.5R0}$ evaluated assuming a steepness of 0.75 (adopted at the 87[th] Meeting as interim limits). The B limit corresponds to a depletion level of $0.077B_0$. Using the 2014 assessment results, the corresponding F/F_{MSY} values are 2.4 and 1.6 for yellowfin and bigeye.	For N. Atlantic swordfish: 0.4 B_{MSY} (interim limit; Rec 13-02)	Biomass: Tropical tunas: 0.4 B_{MSY} (0.5 B_{MSY} for BET) 1.4 F_{MSY} (1.3 F_{MSY} for BET & 1.5 F_{MSY} for SKJ)-(interim limits; Res 12/01 and 13/10)	For tropical tunas and S. Pacific albacore: 0.2 $SB_{F=0}$ ($0.2B_0$) evaluated using recent recruitment levels (adopted at the 2012 annual meeting)
Rebuilding targets	$0.2B_0$ (with 70% probability) in 25 years *	None	Western Atlantic bluefin: 20-year program to rebuild to BMSY (recs. 98-07 and 14-05). Eastern Atl. and Mediterranean bluefin: A 15-year recovery program to reach BMSY with at least 60% probability (Recs 07-05 and 14-04). Past Recommendations: Rec 06-02 established a 10-year rebuilding program for N. Atlantic swordfish to achieve B_{MSY} with greater than 50% probability. Rec. 09-05 established a rebuilding program for N. Atlantic albacore with the implied rebuilding target of B_{MSY} in 10 years.	None	For BET, reducing F to FMSY by 2017 is an implied rebuilding target under CMM 2014-01

Table 2: Kobe II Strategy Matrix, $P(F \leq F_{\mathrm{MSY}})$ and $P(SSB \geq B_{\mathrm{MSY}})$ based on Eastern Atlantic bluefin.

TAC	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
0	33	43	51	60	69	79	89	95	99	100
20	33	42	50	59	67	77	87	94	98	100
40	33	41	50	57	66	75	85	93	97	99
60	33	41	48	56	64	73	83	91	96	99
80	33	40	48	55	62	71	81	89	95	98
100	32	40	46	53	61	69	79	87	94	97
120	32	39	45	52	59	67	76	85	91	96
140	32	38	44	50	57	64	73	82	89	94
160	32	38	43	49	55	62	70	78	86	92
180	32	37	42	47	53	59	67	75	82	89
200	31	36	41	46	51	57	63	71	78	84
220	31	35	40	44	48	53	59	67	73	79
240	28	32	36	40	44	49	54	61	67	72
260	25	29	33	36	40	44	49	54	60	65
280	22	25	29	33	36	40	44	49	54	58
300	19	23	26	30	33	37	40	44	49	53

Table 3: Strategy Matrix in the IOTC format for Setting Management Measures based on Eastern Atlantic bluefin.

Objective	TAC					
	0K	60K	12K	18K	24K	30K
$F_{2022} \leq F_{\mathrm{MSY}}$	1.0	1.0	1.0	1.0	0.91	0.72
$SSB_{2022} \geq B_{\mathrm{MSY}}$	1.0	0.99	0.96	0.89	0.74	0.59
Green Quadrant	1.0	0.99	0.96	0.89	0.72	0.53

Table 4: Strategy Matrix in the IATTC format integrating over assessment uncertainty and by recruitment, catch and selection pattern scenariosbased on Eastern Atlantic bluefin.

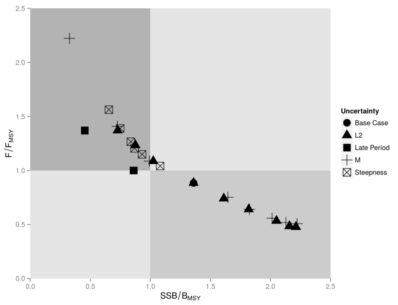
Green by 2022	TAC					
	0K	6K	12K	18K	24K	30K
Combined	0.99	0.98	0.96	0.88	0.72	0.52
Low recruitment	0.99	0.97	0.90	0.79	0.64	0.50
Medium recruitment	1.00	1.00	0.99	0.95	0.74	0.45
High recruitment	1.00	0.99	0.98	0.91	0.77	0.61
Inflated	1.00	0.99	0.99	0.98	0.95	0.85
Reported	0.99	0.98	0.92	0.79	0.48	0.19
Selectivity 2010	0.99	0.98	0.94	0.85	0.69	0.50
Selectivity 2012	0.99	0.99	0.97	0.91	0.74	0.54

Table 5: CCSBT reference set of OMs

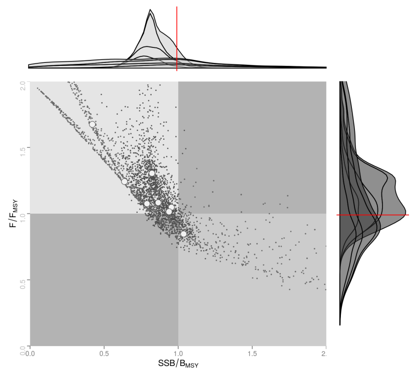
	Levels	CumulN	Values	Prior	Weighting
h	5	5	0.55, 0.64, 0.93, 0.82, 0.9	uniform	obj. fun.
M_0	4	20	0.3, 0.35, 0.4, 0.45	uniform	obj. fun.
M_{10}	3	60	0.07, 0.1, 0.14	uniform	obj. fun.
ω	1	60	1	NA	NA
CPUE	2	120	w.5, w.8	uniform	prior
q age-range	2	240	4-18, 8-12	0.67, 0.33	prior
Sample size	1	240	SQRT	NA	NA

Table 6: Kobe II strategy matrix for yellowfin tuna in the EPO in 2012

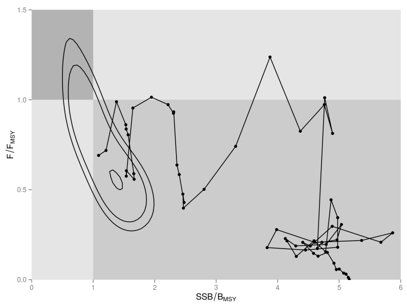
Proposed reference point	**State of nature steepness**	**Variability**	**δ required to ensure the following probability of being below the target or limit**			
			95%	**90%**	**80%**	**50%**
Target $F = F_{MSY}$	Base case	Low	0.972	0.980	0.991	1.010
		High	0.906	0.929	0.957	1.010
	$h = 0.75$	Low	0.604	0.613	0.624	0.644
		High	0.578	0.592	0.610	0.644
Limit $F = 1.4\ F_{MSY}$	Base case	Low	1.361	1.372	1.381	1.415
		High	1.269	1.301	1.323	1.415
	$h = 0.75$	Low	0.809	0.829	0.854	0.902
		High	0.846	0.858	0.873	0.902



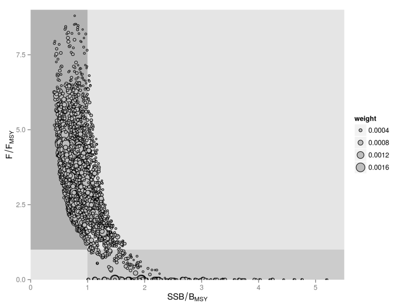
(a) IATTC



(b) ICCAT



(c) IOTC



(d) WCPFC

Figure 2: Example of Kobe Phase Plots, quadrants identify where the stock is overfished (biomass or SSB is less than B_{MSY}) or overfishing is occurring ($F \geq F_{MSY}$) and a target region (where both SSB $\geq SSB_{MSY}$ and $F \leq F_{MSY}$). IATTC example is for the Eastern Pacific bigeye Stock Synthesis assessment, with 26 scenarios represent uncertainty about the values of parameters; IOTC example is for the Indian Ocean albacore Stock Synthesis assessment and 36 scenarios results are contoured to generate a probability density. WCPFC shows the silky shark Stock Synthesis assessment for 2,592 scenarios; the size of the circles correspond to plausibility based on expert judgement. The ICCAT example is for South Atlantic albacore assessment using two biomass dynamic models implementations (ASPIC using maximum likelihood and BSP using Bayesian simulation) with two production functions and two catch per unit effort series; the large circles denote the medians from each assessment run and the small dots individual estimates from Monte Carlo simulations, marginal probability distributions are also shown along the x and y-axis.

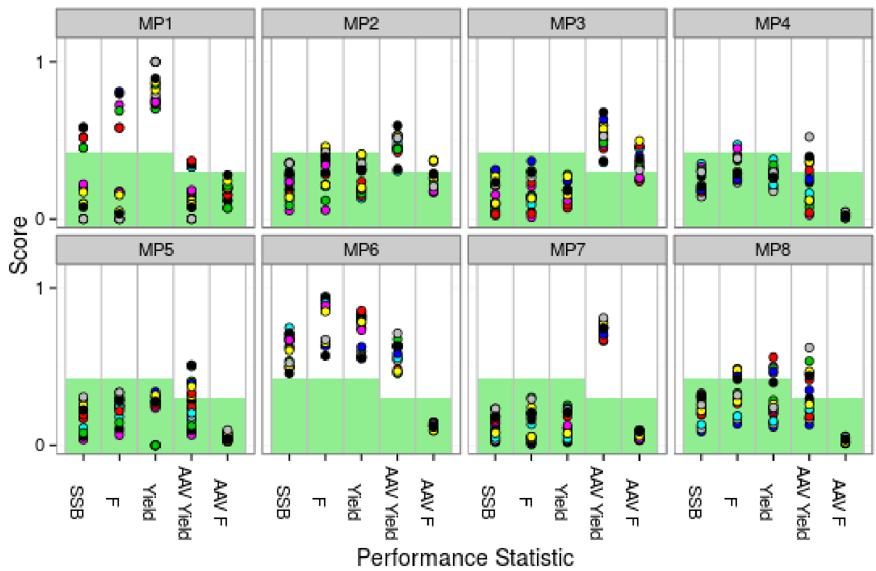


Figure 3: decision plot.

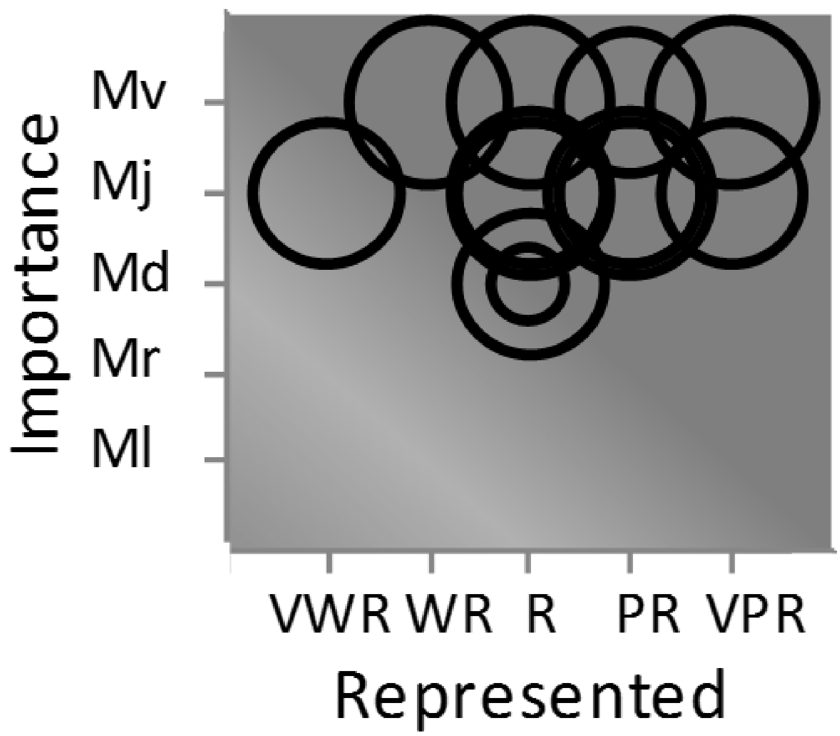


Figure 4: Visualisation of stakeholder views.