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Strategic management decision-making in a complex world: quantifying, understanding, and using trade-offs

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The use of management strategy evaluation (MSE) techniques to inform strategic decision-making is now standard in fisheries management. The technical aspects of MSE, including how to design operating models that represent the managed system and how to simulate future use of management strategies, are well understood and can be readily applied, especially for single-species fisheries. However, MSE evaluations seldom identify strategies that will satisfy all the objectives of decision-makers simultaneously, i.e. each strategy will achieve a different trade-off among the objectives. This study illustrates the basis for identifying management objectives and representing them mathematically using performance measures, as well as how trade-offs among management objectives have been displayed to various audiences who provide input into decision-making. Approaches and experiences are illustrated using case studies. Examples highlight the wide variety of objectives that can be considered using MSE, but that traditional single-species considerations continue to dominate the information provided to decision-makers. The desirability and consequences of having minimum acceptable standards of performance for management strategies, as well as difficulties assigning plausibility ranks to alternative states of nature, are found to be among the major challenges to effective provision of strategic advice on trade-offs among management strategies.

Keywords: decision table, management strategy evaluation, trade-offs.

Introduction

Trade-offs associated with fisheries management have been a component of the advice provided to decision-makers because of the development of quantitative methods within the field. For example, Beverton and Holt (1957) used yield-per-recruit analysis to quantify trade-off between natural mortality and growth associated with different choices for the age at which animals are recruited to a fishery. There is frequently an optimum choice for this age, given that the objective is to maximize yield-per-recruit. However, it is seldom true that there is a "best" management action once multiple objectives are considered.

Since the work of Beverton and Holt, quantitative fisheries science has developed methods for evaluating many types of trade-offs. In the context of single-species fisheries, trade-offs that are routinely quantified include those between:

(i) expected long-term catch (or profit) and risk of the resource dropping below some threshold level of biomass associated with a choice of target level of fishing mortality or biomass (e.g. Deroba and Bence, 2008; Punt *et al*., 2014);

(ii) catch variability and average catch associated with the choice of a harvest control rule (e.g. Bergh and Butterworth, 1987; Deroba and Bence, 2008);

(iii) rate of rebuilding of an overfished stock and catch during the rebuilding period (e.g. Punt and Ralston, 2007; Punt, 2011); and

(iv) between catch by each fleet in a multifleet fishery (e.g. Wang *et al*., 2009), given a constraint on the expected state of the stock.

Once consideration is given to the multispecies nature of fisheries, there are trade-offs among species. These trade-offs can be evaluated using multispecies yield-per-recruit analysis (e.g. Pikitch, 1987) and projections that allow for the dynamic nature of multispecies and/or technical interactions, particularly when species are caught as bycatch in one fishery and targeted in others (e.g. De Oliveira and Butterworth, 2004; Dichmont *et al.*, 2006, 2008, 2013). A more extreme version of the latter situation occurs when the need to rebuild a depleted low productivity stock constrains catches for other more productive and often more valuable species (Hilborn *et al.*, 2004, 2012; Ulrich *et al.*, 2011).

Implications of the target fishing mortality rate or target biomass for a fishery can be expressed as the trade-off between yield of the fishery and impacts on habitat (Dichmont *et al.*, 2013), protected species (Dichmont *et al.*, 2008; Fulton *et al.*, 2014), and other ecosystem components. Pikitch *et al.* (2012) and Smith *et al.* (2011) explore target levels of biomass for small pelagic fisheries at which system-wide yield is maximized, and the trade-off in terms of impacts on the broader ecosystem.

Until recently, conducting analyses to provide the technical basis for quantifying trade-offs has been technically infeasible. However, it is now feasible to explore the consequences of multiple uncertainties simultaneously and represent the results in a probabilistic way, given the advent of management strategy evaluation (MSE; Smith, 1994) methods, as well as the availability of adequate and inexpensive computing resources. Best practices for constructing operating models and scenarios to explore in an MSE are now available (e.g. Punt *et al.*, in press). The ability to quantify trade-offs, particularly using complex models that may make many assumptions and represent a wide range of uncertainties, leads to potentially enormous amounts of outputs, and hence the need to effectively communicate trade-offs.

Trade-off analysis in fisheries, including MSE, falls within the general field of multicriteria decision analysis. The simplest approach for illustrating trade-offs is the decision table. However, a decision table is inadequate to support management decision-making when the decision relates to selecting a management strategy, as shown below. Consequently, the remainder of this study outlines how to select objectives and performance measures for an MSE, as well as how the results of an MSE can be presented to decision-makers. Finally, the study discusses how to use the results from an MSE to select a management strategy.

Decision tables

Decision tables are formal ways to express trade-offs in the face of uncertainty regarding which model of reality (or parameters of a single model) is correct. Construction of a decision table involves selecting a small number (more than about seven makes it difficult to interpret a decision table) of "states of nature" based on an "axis of uncertainty", and a number of management actions. States of nature and management actions represent, respectively, the rows and columns of the decision table (Table 1). Each state of nature needs to be associated with a probability, and the remaining values are performance measures that represent the consequences of applying each management action when each state of nature is true.

Decision tables form a key component of management advice provided for many stocks, including groundfish stocks, off the US west coast. Table 1 summarizes an example of a decision table presented to the Pacific Fishery Management Council (PFMC) for petrale sole (*Eopsetta jordani*) off the US west coast. For this case, natural mortality for females was chosen as the state of nature, and three values for female natural mortality were chosen, respectively, low, median, and high productivity, and hence stock status relative to the unfished level. Management actions were alternative harvest strategies. Two performance measures, spawning biomass and depletion, were reported.

The example in Table 1 illustrates a number of features regarding the use of decision tables to present trade-offs. First, only three states of nature were provided. Guidelines developed by the PFMC for decision tables (PFMC, 2014) suggest that the states of nature be assigned probabilities of 0.25, 0.5, and 0.25 to ensure that decision-makers do not base their decisions on states of nature that may be very unlikely. However, this raises one of the difficulties associated with the use of decision tables, namely how to select the states of nature and how to assign probabilities to them. These difficulties are exacerbated when states of nature are alternative models.

Decision tables are generally framed in terms of a single performance measure, although when there are only a few states of nature, it is possible to show several performance measures in a single decision table (e.g. Table 1). However, when there are multiple performance measures, it becomes difficult to identify patterns in the results. It is

Table 1. Summary table of 4-year projections for petrale sole (*E. jordani*) beginning in 2017 for alternate states of nature based on an axis of uncertainty.

			Low female *M*		**Base-case female *M***		**High female *M***	
			0.25		**0.5**		**0.25**	
	Year	**Catch (mt)**	**Spawning biomass (mt)**	**Depletion**	**Spawning biomass (mt)**	**Depletion**	**Spawning biomass (mt)**	**Depletion**
Strategy 1	2017	3112	10 952	0.282	11 069	0.319	11 233	0.356
	2018	3028	10 801	0.278	10 801	0.311	10 834	0.343
	2019	2940	10 617	0.273	10 543	0.304	10 484	0.332
	2020	2872	10 446	0.269	10 344	0.298	10 235	0.324
Strategy 2	2017	2627	11 017	0.282	11 126	0.319	11 290	0.356
	2018	2629	11 168	0.286	11 149	0.32	11 185	0.353
	2019	2615	11 245	0.288	11 134	0.32	11 075	0.349
	2020	2605	11 289	0.289	11 127	0.319	11 010	0.347
Strategy 3	2017	1711	11 017	0.282	11 126	0.319	11 290	0.356
	2018	1804	11 737	0.301	11 708	0.336	11 736	0.37
	2019	1877	12 351	0.317	12 206	0.35	12 119	0.382
	2020	1941	12 879	0.33	12 646	0.363	12 471	0.393

Columns range over low, mid, and high levels of natural mortality (*M*) and rows range over different assumptions regarding catch levels (source: Stawitz *et al.*, 2015). Depletion is spawning biomass relative to unfished spawning biomass.

common for an MSE to provide tens, if not hundreds, of outputs, many of which may be of interest to decision-makers (see below). Consequently, while decision tables are appropriate for situations such as quantifying the trade-off between catch and population size, they are generally not useful for MSE.

MSE and performance measures

Process for selecting objectives and performance measures

One of the main strengths of MSE is that decision-makers clarify their objectives. Punt *et al.* (in press) noted that objectives for fisheries management can be categorized as either "conceptual" ("strategic") or "operational" ("tactical"). Conceptual objectives are generic, high-level policy goals. To be included in an MSE, conceptual objectives need to be converted into operational objectives (expressed in terms of the values for performance measures). This usually involves translating each conceptual objective into one or more operational objective(s) and performance measure(s).

A key component of an MSE, the results of which are intended to be presented to a group of decision-makers, is therefore to effectively identify strategic and conceptual objectives and performance measures that capture those objectives. Management objectives are likely to be conflicting. Almost by definition, objectives stated by decision-makers cannot be "wrong" and should be given serious consideration even if there is no consensus among decision-makers regarding the appropriateness of some of the objectives. Nevertheless, the process of elucidating objectives should emphasize that they be quantifiable through the operating models that are part of the MSE. Mapstone *et al.* (2008) provide a "gold standard" for elucidating objectives and quantifying them using performance measures in their evaluation of closure regimes for Australia's Great Barrier Reef. Representatives of the research team conducting the MSE met separately with each stakeholder group several times over 2 years, then held workshops that brought all the stakeholders together to ensure that all objectives were collectively understood (though perhaps not agreed). These workshops also reviewed how objectives were to be expressed as performance measures that could be output by the MSE.

The approach taken by Mapstone *et al.* (2008) was very resource intensive, which may explain why their approach has seldom been adopted. A more common approach to identifying objectives and performance measures is to separate the process of identifying management objectives (which tend to be broad, vague, and likely inconsistent) from the process of translating those objectives into performance measures. This is the approach taken by the Scientific Committee of the International Whaling Commission (IWC SC). In this case, the Commission identified and ranked objectives (Table 2), and the IWC SC developed quantitative performance measures to represent the objectives.

A third approach, adopted for the MSE for Pacific sardine (*Sardinops sagax*) off the US west coast, recognized that management objectives are largely "prespecified" through National Standards that are part of the US Magnuson-Stevens Act, along with guidelines adopted by the National Marine Fisheries Service. The choice of performance measures for this case involved an iterative process whereby an initial set of performance measures was selected by analysts conducting the MSE (PFMC, 2013), and those performance measures were modified based on input from decision-makers (the PFMC), their scientific and policy advisors, as well as members of stakeholder groups (industry and environmental non-governmental organizations). Compared with performance measures that were originally suggested, the final set (Table 3) included average catches based on all years rather than just those years when the fishery was open. Several additional performance measures quantified the extent of variation in catch and biomass, particularly how often catch or biomass is likely to drop to low levels.

Performance measures in practice

Punt *et al.* (in press) note that measures used to evaluate the performance of alternative candidate management strategies should be chosen so that they are easy for decision-makers and stakeholders to interpret (Francis and Shotton, 1997; Peterman, 2004). Butterworth and Punt (1999) comment that standard deviations or coefficients of variation of catch limits are difficult for many stakeholders to understand. Experience suggests that stakeholders find it much easier to relate to performance measures, such as the fraction of years during which catch is less than some desirable level, than more complex metrics, such as standard deviation of catch over time.

There should not be a large number of performance measures. For example, Table 3 includes many performance measures, but the final decision hinged on the values for only a few of these. The following sections outline typical performance measures that are reported in various types of MSEs, based on the set of MSEs in Table 4.

Single-species MSEs

Most of the MSEs conducted to date, as well as the majority of those that have been used for actual fishery management decision-making,

Table 2. Objectives for commercial and aboriginal subsistence whaling (Kell *et al.*, 2006).

Objective	Examples of performance measures
Commercial whaling	
Achieve an acceptable risk level that a stock not be depleted (at a certain level of probability) below some chosen level (e.g. some fraction of its carrying capacity), so that the risk of extinction of the stock is not seriously increased by exploitation[a]	Lowest population size over 100 years (median and fifth percentage over simulations)
Make possible the highest continuing yield from the stock	Average catch over 100 years (median and fifth percentage over simulations)
Achieve stable catch limits	Annual average variation in catch limits (median over simulations)
Aboriginal subsistence whaling	
Ensure that hunts do not seriously increase risks of extinction and that hunted whale populations move to (if they are not already there), and are then maintained at, healthy, relatively high levels	Lowest population size over 100 years and ratio of total population in 100 years to the current population size (median and fifth percentage over simulations)
Enable native people to hunt whales at levels appropriate to cultural and nutritional requirements in the long-term	Total number of strikes divided by the total need (median and fifth percentage over simulations)

[a]Assigned the highest priority by the International Whaling Commission.

have focused on single species and their management. Performance measures for single-species MSEs mainly focus on three dimensions of performance: (i) catches, (ii) biomass of the target species, and (iii) variability of catch (Table 5). However, other performance measures include those that relate to profits (often in addition to catches). Performance measures unique to specific cases and of

Table 3. Performance measures for the MSE for Pacific sardine used for decision-making (Hurtado-Ferro and Punt, 2014).

Average catch (all years)[a]
Standard deviation of catch (all years)[a]
Average catch (all years for which the catch is non-zero)
Standard deviation of catch (all years for which the catch is non-zero)
Mean biomass (spawning and 1+ biomass)
Standard deviation (spawning and 1+ biomass)
Percentage (1+) biomass >400 000 t
Percentage of years with no catch (or catch below 50 000 t)
Median catch (all years)[b]
Median biomass (spawning and 1+ biomass)
Average number of consecutive years with zero catch
How often the exploitation rate is set to its minimum/maximum value
Average number of consecutive years the exploitation rate equals its minimum/maximum value
Mean age of the population
Mean age of the catch
Mean and maximum number of consecutive years in which catch <50 000 t[a]
Mean and maximum number of consecutive years in which 1+ biomass <400 000 t[a]

[a]New performance measure.
[b]Modified from the median catch for all years for which the catch is non-zero.

Table 4. Examples of MSEs by MSE type, the results of which have been presented to decision-makers.

MSE type	Key references
Single-species MSEs	
Australia's southeast scalefish and shark fishery	Little *et al.* (2011) (A1); Klaer *et al.* (2012) (A2)
Gray whales off west coast of North America	IWC (2005) (B1)
Small pelagic fish off southern Australia	Smith *et al.* (2015) (C1)
Sardine off the west coast of the United States	Hurtado-Ferro and Punt (2014) (D1)
Coral trout off the Great Barrier reef	Mapstone *et al.* (2008) (E1)
Multispecies; multistock; multisector MSEs	
Anchovy-sardine off South Africa	De Oliveira and Butterworth (2004) (F1)
Merluccius capenesis and *M. paradoxus* off South Africa	Rademeyer *et al.* (2008) (G1)
Australia's northern prawn fishery	Dichmont *et al.* (2006) (H1)
Minke whales in the western North Pacific	IWC (2014) (I1)
Coral trout and red throat emperor off eastern Australia	Little *et al.* (2009) (J1)
Ecosystem MSEs	
Australia's northern prawn fishery	Dichmont *et al.*, (2008, 2013) (K1, K2)
Australia's Torres Strait rock lobster fishery	Plagányi *et al.* (2013b) (L1)
Australia's southeast scalefish and shark fishery	Fulton *et al.* (2014) (M1)
Penguins and small pelagic fish off South Africa	Robinson *et al.* (2015) (N1)

Table 5. Typical performance measures included in MSEs. The cases are defined in Table 4.

Performance measures	Cases
Target species (catch and profit)	
Catch	A1[a], A2[b,c], C1[c], D1, E1[c], F1, G1[a], I1[d], J1[c], L1[d], M1[e]
Catch variability	A2, B1, D1, E1, F1, G1, H1, I1
Catch relative to need	B1
Probability catch < threshold value	D1, H1
Lowest catch	H1
Probability of catching big fish	E1
Number of consecutive years catch < threshold value	D1
Average size of catch	M1
Catch rate	M1
Catch rate relative to the reference catch rate	A1[a], E1[c,d], G1[f], J1[c]
Discounted catch/revenue	H1, M1
Costs (research, enforcement)	M1
Profit	K1, L1[d], M1[e]
Profit variability	K1
Profit per tonne/per unit effort	M1
Catch composition (maximum proportion of one species)	M1
Target species (population size)	
Biomass[g]	D1, G1[a], I1, M1
Biomass[g] relative to unfished biomass	A1[a], A2[c], B1[f], C1[c], E1[c]
Biomass relative to reference biomass	K1, K2
Biomass[g] relative to initial biomass	B1[f], G1[f], J1[c], L1[f]
Lowest biomass relative to unfished biomass	A2, I1
Lowest biomass	I1
Probability of local depletion	L1
Probability biomass < (or >) threshold value	A2, C1[c], D1, F1, K1
Number of consecutive years biomass < (or >) threshold value	D1
Bycatch species/threatened species	
Biomass of non-target species	K2, M1
Number of at-risk species	K2
Biomass of at-risk species	M1
Probability of species at risk	K2
Interactions with threatened species	M1
Other ecosystem components and fishing community impacts	
Public image	M1
Proportion of total habitat fished	K1, K2, M1
Benthic biomass relative to unfished benthic biomass	K1, M1
Gastropod biomass relative to unfished gastropod biomass	K1
Predator numbers/biomass	N1[a], M1
Employment	L1[a]
Access and distribution equity among sectors and ports	L1, M1
Conflict among sectors	L1, M1
Effort	K2, M1
Displaced effort	K2
Amount of quota trading	M1

Performance measures are computed over the entire projection period unless stated otherwise.
[a]Time-trajectory, [b]average, [c]last few years, [d]by fishery sector, [e]summed over all species; [f]final year, or [g]numbers; biomass can be available biomass, total biomass, or spawning biomass.

major interest to a subset of decision-makers, such as probability of a recreational fisher catching a large fish (Mapstone *et al.*, 2008), may also be reported even for single-species MSEs.

Many of the outputs from operating models are in the form of time-series (e.g. catch and biomass), and it is necessary to synthesize these time-series to develop performance measures. Ways of synthesizing time-series range from taking an average over time, finding the lowest value, and reporting the value of the time-series for the last year of the projection period (or the average over the last few years of the projection period). Scaling of performance measures becomes more complex when the underlying biological system is not stationary, e.g. because of climate change. Approaches to overcome this problem include scaling time-trajectories of operating model outputs by time-trajectories of these outputs for a no-fishing situation (e.g. A'mar *et al.*, 2009a, b, 2010) or a situation where there is no fishing and the system is stationary (e.g. Plagányi *et al.*, 2013a).

Several methods for reporting variation in catch have been developed (Table 5), but the author's experience is that the probability of catch decreasing below a critical value tends to be the easiest for most decision-makers to understand.

Multispecies MSEs

The multispecies MSEs in Table 4 report the same performance measures as single-species MSEs (Table 5), except that the number of performance measures is larger and it is necessary to integrate results (e.g. profit) over species. Multispecies MSEs tend to report performance measures to illustrate trade-offs between species, e.g. an increase in the harvest of one species may only be possible if the harvest of another species is reduced.

Ecosystem MSEs

Ecosystem MSEs typically include the same performance measures as single- and multispecies MSEs (Table 5), but there is an even greater need to summarize results over species, thereby losing detail at the species level to obtain a better impression of the impact of the performance of candidate management strategies across a wider range of objectives. The ecosystem MSEs in Table 4 reported a very wide range of performance measures, and there was little consistency in performance measures reported by the ecosystem MSEs (Table 5).

Performance measures reported by the ecosystem MSEs include metrics related to the status of non-target species, habitat, and threatened and endangered species. Performance measures for non-target species and habitat tend to show biomass relative to either the unfished state of the system or the state of the system when management strategies are to be first applied. In contrast, interest for threatened and endangered species is whether the management strategies delay their recovery (e.g. Plagányi and Butterworth, 2012).

Some of the ecosystem MSEs provide information about the broader impacts of the choice of management strategies, including whether they have detrimental impacts on employment, or increase the amount of conflict among stakeholder groups. Performance measures related to broader impacts can include costs associated with monitoring and management, as well as those that summarize performance of the management system itself (e.g. "amount of quota trading" and "public image"; Table 5).

Performance measures and scenarios

Most MSEs involve many scenarios (A scenario in this context is the combination of assumptions regarding the biological and fishery aspects of the system, assumptions related to future effects such as climate change, and assumptions related to future data collection), further increasing the number of values decision-makers need to consider. Consequently, it is common when applying MSE to assign plausibility ranks to each scenario (cf. IWC, 2012a) or to average performance measures over scenarios after assigning each scenario a weight. Alternatively, high plausibility scenarios can be assigned to a reference set and the remaining scenarios to a robustness set, with the focus for decision-making on the reference set (Rademeyer *et al.*, 2007). Performance measures for each scenario within the reference set are weighted based on the weight assigned to the scenario. However, this involves selecting quantitative weights upon which agreement is likely to be difficult. Moreover, weighted performance measures may obscure low plausibility trials for which performance is very poor (Rademeyer *et al.*, 2007).

The IWC has adopted a set of guidelines for interpreting the results of scenarios to evaluate management strategies for commercial whaling. Specifically, trials are assigned to one of three categories ("high plausibility", "medium plausibility", or "low plausibility") by the IWC SC (IWC, 2012a). The required conservation performance of "acceptable" management strategies, expressed in terms of the values for performance measures, is prespecified for each category, which essentially [though not entirely—see IWC (2012a) for details] automates the process of selecting a "best" management strategy (see below). In an effort to provide an improvement to simply selecting plausibility ranks based on expert judgement, Butterworth *et al.* (1996) proposed four sets of criteria with which plausibility ranks might be assessed. Although this approach was presented to the IWC SC, it was never adopted, and weights are almost always assigned based on expert judgement at the IWC SC.

Using plots to summarize performance

It is highly likely that some of the objectives will be in conflict to some extent, and one aim of MSE is to highlight trade-offs among objectives as quantified using performance measures. As emphasized by Rademeyer *et al.* (2007), the basis for selecting a management strategy has to be clear to all stakeholders and should be made as simple as can be justified.

If there are very few performance measures, and candidate management strategies depend on a few tuning parameters, it is possible to show trade-offs across the entire spectrum of management strategies. Figure 1 shows that increased monitoring efforts (one dimension of the management strategy) may allow higher catches of anchovy (*Engraulis capensis*) off South Africa for the same level of risk. Each of the curves in Figure 1 was constructed by varying a tuning parameter of the management strategy. Figure 2 also shows results for the fishery for anchovy and sardine (*S. sagax*) off South Africa where the trade-off is between catches of the two species, with the points along the curve selected so that the risk to both anchovy and sardine is constant (but different between species because of, for example, among species differences in recruitment variation).

Typically, a large number of performance measures are considered in MSEs (see Table 5), and several graphical approaches have been developed to help decision-makers view and understand trade-offs. The simplest types of outputs from an MSE are time-trajectories of catch and abundance (for single-species MSEs). Such outputs are valuable to understand the generic behaviour of the management strategies, but usually lead to substantial amounts of information, making decision-making very difficult if there are many candidate management strategies. However, examination of time-trajectories of model outputs is valuable when the number

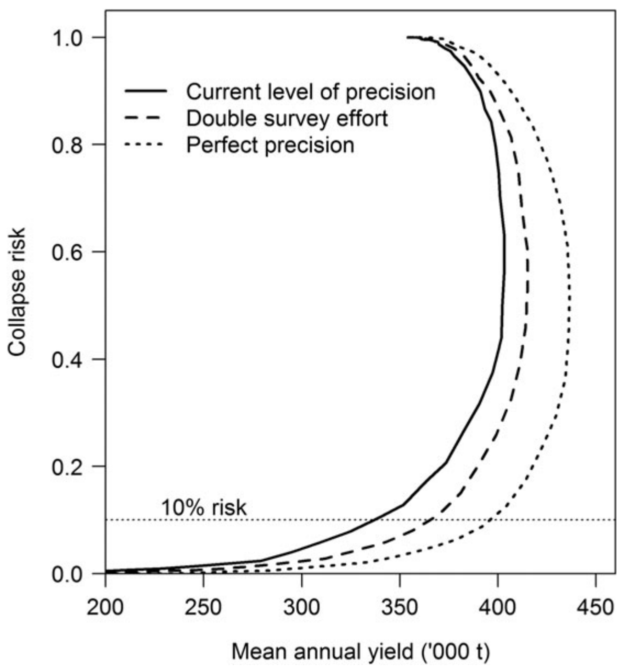

Figure 1. Relationship between risk and reward for South African anchovy ("collapse" is defined here as the spawning biomass falling below 10% of its average unexploited level, and risk reports the probability of that happening at least once during a 20-year period). Each line indicates a different level of survey precision [modified from Bergh and Butterworth (1987)].

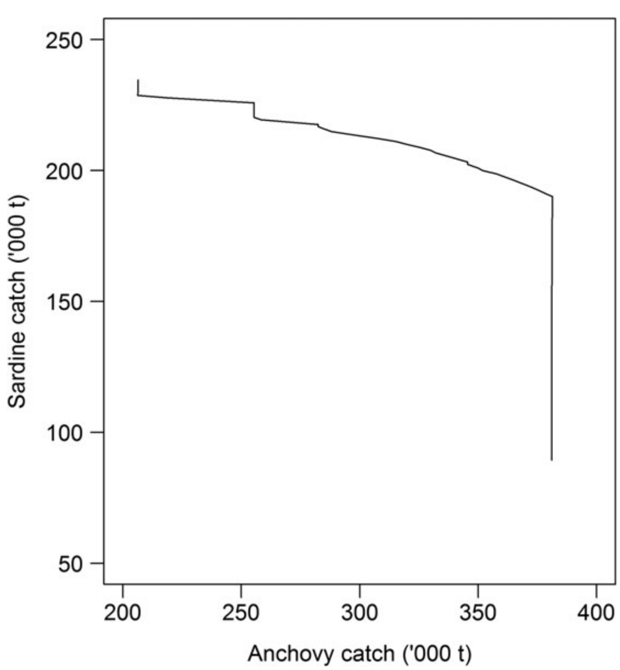

Figure 2. Trade-off plot for South Africa anchovy and sardine. The line indicates the locus of expected catch of anchovy and sardine achieved by changing one of the tuning parameters of management strategy (data provided by C. de Moor, University of Cape Town, pers. comm.).

of candidate management strategies has been reduced to a small number (e.g. Fulton *et al.*, 2014).

A simple way to express the values for performance measures is through histograms (Figure 3, upper panels). For histograms of performance measures to be most useful, all the performance measures should be defined, so that higher (or lower) values correspond to the best performance. Consequently, one of the original performance measures for Pacific sardine, "percentage of years with zero catch", was transformed into an alternative performance measure ("percentage of years with a non-zero catch"), so that larger values corresponded to better performance. Management strategy "M" performs poorer than all the other management strategies, except for the first performance measure (average catch). Most of the bars in the upper panels of Figure 3 are of similar height, which makes comparisons difficult among management strategies. Differences in the values for performance measures among management strategies can be easier to assess if these values are expressed relative to one (e.g. the *status quo*) management strategy. The lower panels of Figure 3 show the results in the upper panels expressed relative to those for the "HG J" management strategy.

Figure 3 provides the values for performance measures, but does not provide an easy way to evaluate trade-offs. Figure 4a–c shows the same information in Figure 3, but in the form of trade-off plots. Better performance in these plots is indicated by values towards the upper right corner of each panel. Values for two of the performance measures are highlighted in Figure 4. Management strategy "M" (red circles in Figure 4) is noteworthy in that it is close to the lower left corner of each panel. This strategy is "dominated" in that there are several management strategies that achieve equal or better performance on all performance measures, suggesting that this management strategy is inferior to some of the others.

A disadvantage of trade-off plots is that they can only show results for two variables. Kite diagrams (e.g. Figure 4d) show trade-offs among multiple performance measures, although care should be taken not to display too many (>6) management strategies on the same diagram. Fulton *et al.* (2014) summarized the performance of six management strategies across multiple dimensions of performance using kite diagrams where each vertex was a performance measure that synthesized performance over each of five categories of objectives (environment, industry, certainty, social, and management).

Figures 3 and 4 show results for means over simulations and do not show the between-replicate uncertainty. This can be achieved using "Zeh plots" [named after Judy Zeh (Professor Emeritus in the Department of Statistics, University of Washington) who appears the first to have suggested this type of plot). These plots display the median and various percentiles for the performance measures. Zeh plots have been extended by Hurtado-Ferro *et al.* (2014) using violin plots to convey the entire distribution of outcomes. Figure 5 shows a Zeh plot for an MSE evaluating management strategies for Australia's northern prawn fishery. This MSE involved performance measures related to the target species as well as to broader ecosystem objectives. Zeh plots have been used in MSEs as diverse as those of Klaer *et al.* (2012), Rademeyer *et al.* (2008), and Dichmont *et al.* (2008).

Selecting among management strategies

The ideal way to select among management strategies is to (i) define a utility function that balances the various factors and (ii) find the management strategy that achieves maximum utility. However, efforts to base MSEs on utility functions have generally been unsuccessful because decision-makers (and stakeholder groups) wish to

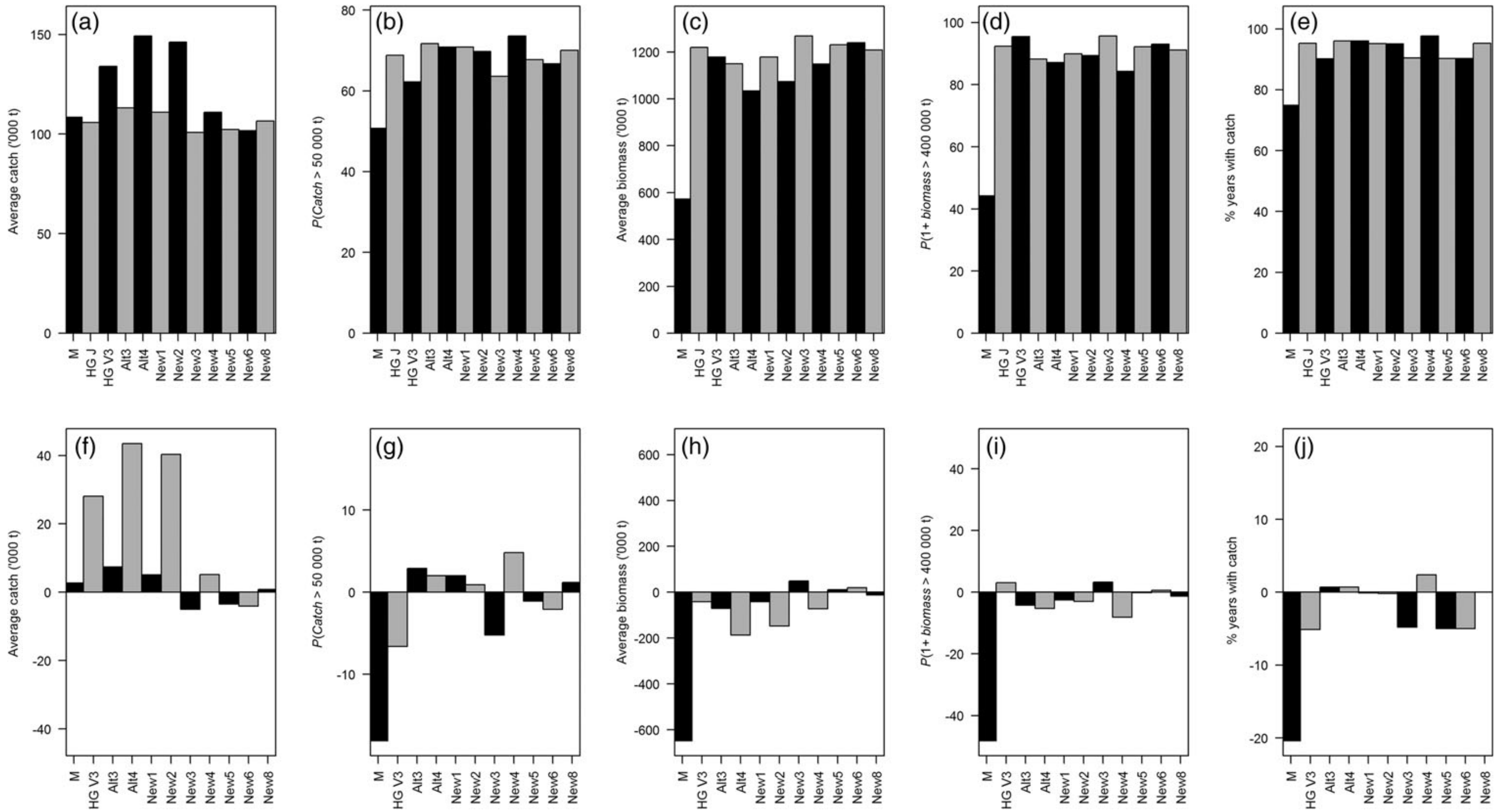

Figure 3. Values for five performance measures for the MSE conducted to evaluate candidate management strategies for the northern subpopulation of Pacific sardine (Hurtado-Ferro and Punt, 2014). The definitions for the management strategies and the performance measures are given by Hurtado-Ferro and Punt (2014). The upper panels show the values for the performance measures by management strategy and the lower panels show the values for the performance measures as differences from the “HG J” strategy.

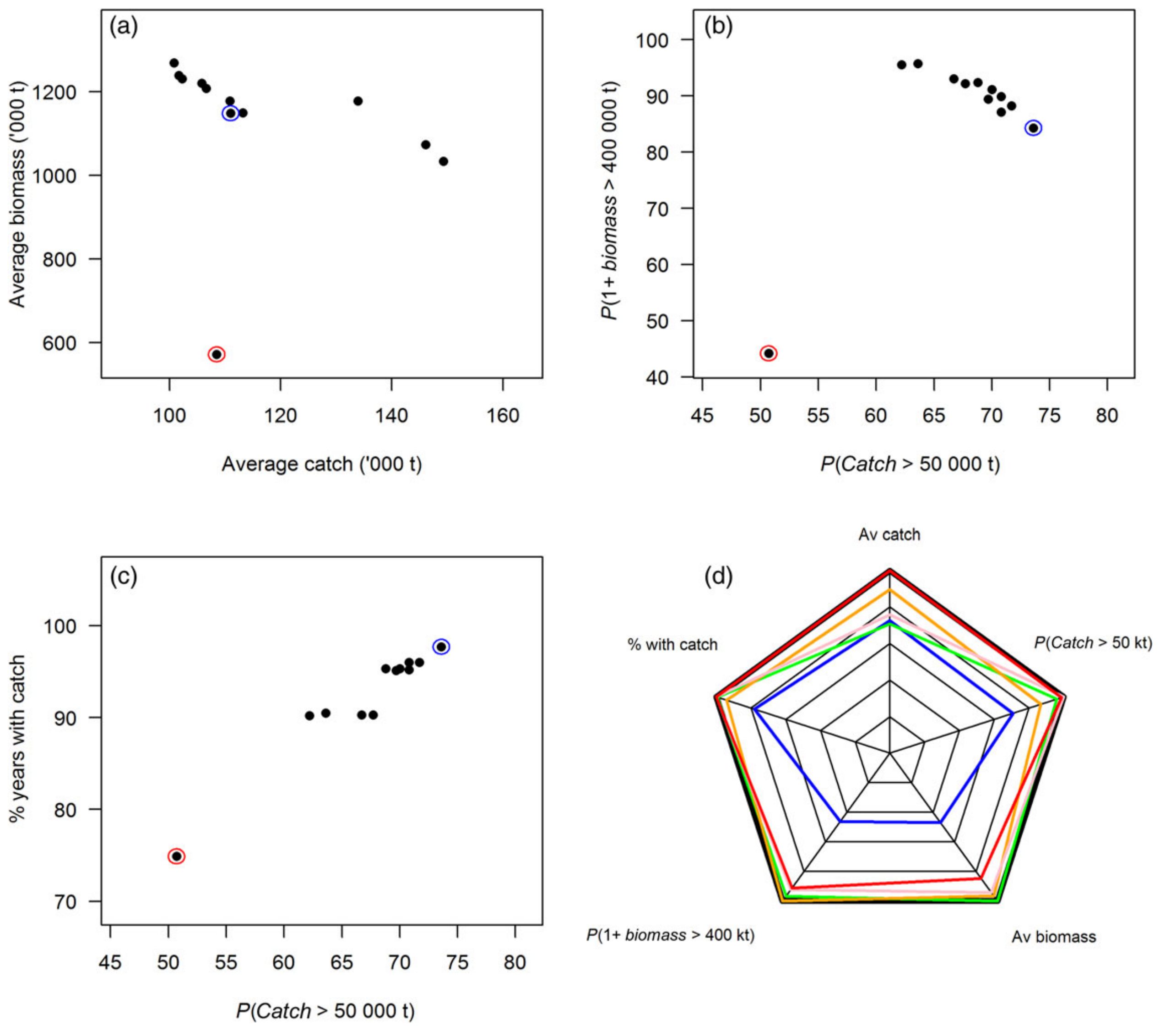

Figure 4. Trade-off plots (a–c) for the northern subpopulation of Pacific sardine. The circled values in (a–c) denote the "M" (red) and "New4" (blue) management strategies. (d) Kite plot illustrating the trade-offs achieved by five of the management strategies (randomly selected).

see how well each candidate management strategy achieves each objective and how they trade-off (Punt *et al.*, in press). A primary reason for the lack of interest in the use of utility functions is that relative weights among the objectives are often not well specified and usually differ among decision-makers.

The first step in the process of selecting a management strategy should be to explain all the options to decision-makers and place the management strategies evaluated in the context of current management arrangements (Dowling *et al.*, 2008). Current management arrangements can be considered to be the *status quo* and hence a default choice if there is no evidence that alternative management strategies perform markedly better. The second step in the selection process should be to eliminate any "dominated" management strategies (e.g. "M" in Figure 4) to reduce the number of options as quickly as possible.

There are two basic approaches to selecting among management strategies: (i) "trading-off" and (ii) "satisficing" (Miller and Shelton, 2010). Satisficing involves specifying minimum performance standards for all (or a subset) of the performance measures and only considering management strategies that satisfy those standards. In contrast, trading-off acknowledges that any minimum performance standards will always be somewhat arbitrary, and that decision-makers should attempt to find management strategies that achieve the best balance among performance measures (and hence objectives).

It may help the decision process if decision-makers can agree on acceptable performance for each performance measure (or at least a subset of those). For example, Mapstone *et al.* (2008) document desirable levels for a range of performance measures identified by stakeholder groups. However, Mapstone *et al.* (2008) were unable to identify quantitative levels of desirable performance for all performance measures considered, with the desirable states noted to be "as high as possible" for performance measures such as average catch. Acceptable values for performance measures may reflect goals established by policy. For example, the Australian harvest strategy policy (DAFF, 2007) specifies that there be <10% chance of a stock being below the limit reference point (which is generally set at 20% of the unfished spawning biomass, i.e. $0.2B_0$). Consequently, Smith *et al.* (2015) only provided results for management strategies

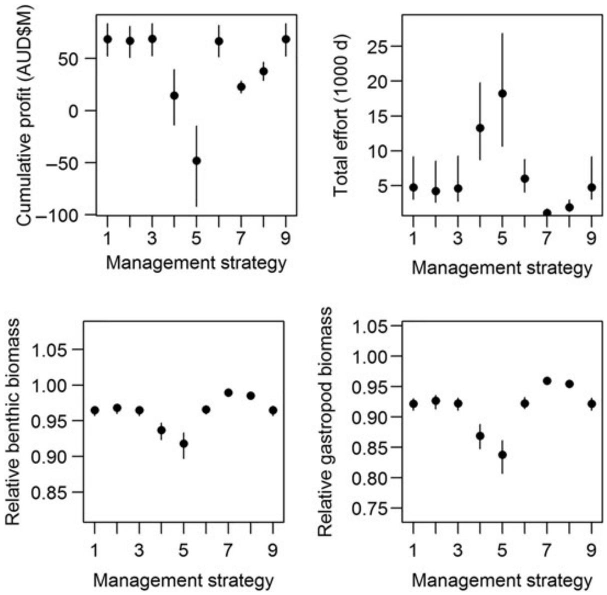

Figure 5. Zeh plots comparing nine management strategies for Australia's northern prawn fishery. The points indicate distribution medians and the lines cover 90% of the distributions for each performance measure across replicates.

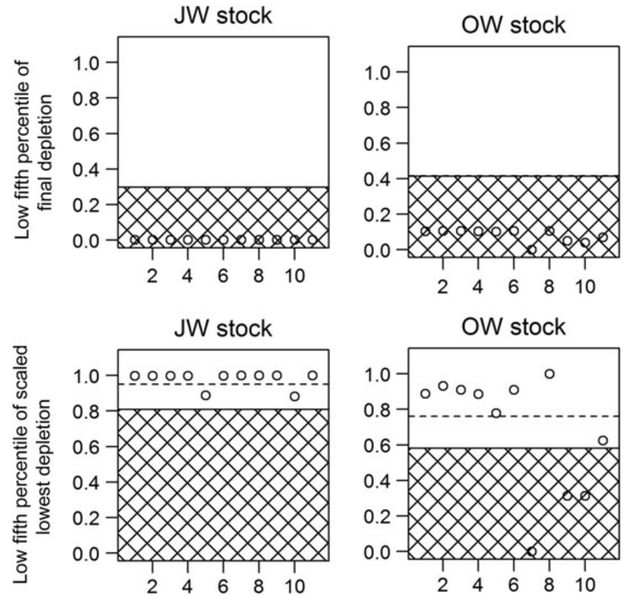

Figure 6. Performance plot for two of the stocks (JW and OW) identified during the evaluation of management strategies for the western North Pacific minke whales (left and right panels, respectively). The upper panels summarize performance relative to final depletion and the lower panels relative to lowest depletion. The labels on the *x*-axis refer to management strategy variants. The dashed line defines acceptable performance (performance measure values above the dotted line correspond to better performance than the threshold for acceptable conservation performance), whereas the hashed area identifies a region of unacceptable performance. The region between the dashed line and the hashed area represents a region where performance is not acceptable, but a management strategy could be selected if it performs much better than the acceptable management strategies for other performance measures.

that satisfied this policy goal in their evaluation of harvest control rules for the Australian small pelagic fishery.

Policy goal constraints also exist in other jurisdictions. For example, in the United States, accountability measures and annual catch limits need to be reviewed (and modified, if needed) if annual catch limits are exceeded more than once in 4 years (NMFS, 2012), while the time to rebuild stocks declared to be overfished is also prescribed (NMFS, 2012). The IWC SC uses MSE to evaluate management strategies for commercial whaling and has developed a set of guidelines (IWC, 2012a) that impose minimum performance standards in terms of conservation. Specifically, no candidate management strategies can be adopted that performs poorer than the "catch limit algorithm" (CLA; IWC, 2012b) if the CLA was applied to a situation that mimics the case under consideration, but there was no uncertainty regarding stock structure. Figure 6 shows an example of the IWC's approach for identifying management strategies for minke whales (*Balaenoptera bonaerensis*) in the western North Pacific. This example shows results for 11 management strategies. "Acceptable" conservation performance corresponds to either the minimum population size being higher than that expected under the CLA or the final population size after 100 years of simulated management being higher than that achieved by the CLA for all stocks in the system. Of the 11 management strategies in Figure 6, only six satisfy these performance standards. None of the management strategies satisfy the performance standard for final depletion for the Sea of Japan west (JW) stock, but all but two management strategies (5 and 10) satisfy the performance standard for lowest depletion for this stock. All the management strategies again fail to satisfy the performance standard for final depletion for the offshore west (OW) stock, but management strategies 1–6 and 8 satisfy the performance standard for the lowest depletion for the OW stock. Management strategies need to perform adequately for all stocks, so in this case, management strategies 1, 2, 3, 4, 6, and 8 would be considered to perform adequately in terms of conservation performance and would be considered further (IWC, 2012a).

Performance standards related, for example, to conservation performance, limit the set of management strategies that can be adopted. Having such standards means that management strategies that just fail to satisfy the minimum performance standards, but achieve better overall performance than the strategies that do satisfy these standards, cannot be considered for adoption. Consequently, the IWC SC allows some management strategies that just fail the conservation performance standards (e.g. strategy 5 in Figure 1) to be considered further.

The selection among the management strategies, or those strategies that have acceptable performance when "satisficing" is implemented, is generally qualitative (decision-makers implicitly weighting the various performance measures). However, formal processes for making decisions given multiple performance measures exist, even if they appear not to have been used in the cases explored in this study. Specifically, multicriteria decision-making (MCDM) is a subfield of operations research that relates to assisting decision-makers.

One MCDM approach that was recommended for use by the IWC was the ELECTRE algorithm. This algorithm was developed by Roy and Vincke (1981) and involves selecting the option (a management strategy) from a set of options that is better than the other options in terms of most of the performance measures, but is not disastrously bad for any of them. An advantage of the ELECTRE algorithm is that the differences in performance among options are expressed as ranks rather than as absolute values. However, it does require that each performance measure be weighted. Punt (1992) explored the use of the ELECTRE algorithm for comparing among candidate management strategies for commercial whaling, and Cooke (1992) provided an alternative MCDM approach for automatically selecting among management strategies. However, ultimately, the IWC SC and the Commission itself preferred to use "human integration" rather than any form of automatic selection method.

Best practice for evaluating trade-offs and some next steps

The key activity when quantifying, understanding, and using trade-offs in relation to selecting among management options or management strategies is to fully involve stakeholders and decision-makers. This will not be a one-time exercise, but will likely be an iterative process where the analysts interact with and respond to the needs of decision-makers. While it is rare to be able to implement the process of Mapstone *et al.* (2008), given limited resources, serious consideration should be given to doing so, given the potential cost of adopting a management strategy that fails to deliver or perhaps, even worse, adopting a management strategy whose objectives differ from those of the decision-makers. To date, only MSEs conducted in Australia appear to have attempted to fully engage stakeholder communities and decision-makers. One possible reason for this is that many of the Australian fisheries already involve some form of co-management, which means that stakeholder groups are more familiar with the quantitative tools used for MSE as well as making (fisheries) management decisions, given uncertainty regarding the state of the system and future outcomes.

Effectively capturing the range of objectives is key to selecting a management strategy, but also when designing the management strategy. For example, developing a single-species MSE when the objectives involve broader considerations will similarly lead to frustration and likely failure. Ultimately, stakeholder consultation should occur at the start of the development of an MSE project to ensure that the MSE is directed towards appropriate ends. However, it is prudent to conduct a data inventory before initiating this consultation process to ensure that there are sufficient data, so that there is some chance of reliably predicting the consequence of management strategies.

It is easy to select too many performance measures, many of which will be highly correlated (Figure 4c). The decision-making process is made considerably simpler if performance measures can be reduced to the smallest number possible. Care should, however, be taken to explain why a proposed performance measure is not presented even if it is scientifically obvious, because a decision-maker may feel "deceived" if "their" performance measure is discarded.

There is often a desire to develop minimum performance standards for a few objectives rather than trade-off performance across various objectives. This is sometimes necessary in light of constraints imposed by policy. However, "satisficing" needs to be implemented carefully; decision-makers particularly need to be aware of the constraints imposed by doing so. Similarly, weighting of scenarios may initially seem desirable, but, in general, it has proved very hard to assign weights to all scenarios in an MSE. Consequently, this author prefers the approach adopted by the IWC SC of assigning scenarios to broad categories of plausibility and essentially treating all scenarios within a category as equally plausible. However, even assigning scenarios to categories of plausibility can be difficult; consequently, the IWC includes a "no agreement" category (IWC, 2012a).

This study has shown the diversity of ways in which results of an MSE can be displayed. It is easy, therefore, to create more information than decision-makers can usefully process. Consequently, there needs to be an investment of time in working with decision-makers to ensure that they understand what they are being presented. It is not unusual for decision-makers to ask analysts their opinion on which strategy is best. This request should not be answered because (i) there is rarely, if ever, a scientifically optimal management strategy, (ii) the point of conducting the MSE is to identify trade-offs and provide decision-makers the ability to make policy decisions, and (iii) once scientists enter the decision-making arena, they become advocates, and the credibility of the entire MSE may be lost.

It is the author's experience that decision-makers may wish to be able to modify management strategies "on the fly", e.g. combining their favourite aspects of two candidate management strategies. Having results available for many candidate management strategies may, therefore, help to facilitate the decision process.

Overall, this study shows that there are many ways in which results of MSEs are presented to decision-makers and how decision-makers and analysts interact to ensure that complex MSE outputs are summarized. However, MSEs have been conducted primarily by biologists and mathematical modellers, whereas the problem under consideration is one of MCDM. Although experiences using MCDM techniques within MSE have not been very successful to date, this is a rapidly evolving field, and efforts should be made to provide decision-makers with techniques developed to select among options when there are many attributes.

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