

## REJOINDER: UNCERTAINTY AND DECISION MAKING

As we (Halpern *et al.* 2006) and Mangel (2006) point out, there are essentially two types of numerical uncertainty – one type can be removed with more data (epistemic uncertainty) and the other type cannot (natural variation or aleatory uncertainty). Biological ignorance, *sensu* Mangel, is simply a combination of these two types. In the context of choosing between management options, the techniques we described in our paper can deal with both types of uncertainty. Probability bounds address both types of uncertainty explicitly in a probabilistic framework. Other bounding techniques, such as interval and info-gap analyses, subsume both types of uncertainty within bounds. While we recognize that the mathematical notation for techniques such as info-gap can be an initial challenge, info-gap is conceptually straightforward. The analysis of robustness using info-gap simply asks: which is the best management option if the model's parameters are  $x$  per cent worse than expected? By plotting the management outcome, e.g. extinction probability vs.  $x$  for each management option, one can find the option that provides an acceptable outcome and is at the same time most robust to uncertainty. Ignoring uncertainty can have profound implications. As pointed out in our paper, management decisions can be suboptimal if uncertainty is ignored.

Although we agree with Mangel that our criterion of metapopulation persistence (i.e. the species does not go extinct) is not particularly conservative for achieving fisheries management goals, it is a reasonable minimum criterion for conservation, and the approaches to evaluating uncertainty that we describe can easily be applied to fisheries population models if one wants to minimize the chance a stock falls below a certain level (or quasi-extinction).

What Mangel clearly exposes with his comment is that decision making under uncertainty is not always an objective problem that can be solved exclusively with scientific information. Management and conservation are necessarily value-driven activities where people decide how much of something they want or are willing to risk losing. Is our objective to minimize the risk of a catastrophic outcome such as extinction or the risk of an unfavourable yield such as a poor harvest, or a combination of the two? These are decisions that need to be hammered out during a problem definition phase, which is often the hardest part of any environmental decision making. While different groups will define the problem in different ways, dealing with this higher level of uncertainty, i.e. problem definition uncertainty, is beyond the scope of our work.

The info-gap model presented in our paper assumes a risk-averse decision maker at the outset. Other methods of

uncertainty analysis, such as precise probability distributions and probability bounds, require positions on acceptable levels of risk and attitudes to risk in order to make a final decision. But even when a decision is based upon a model, no particular outcome can be guaranteed. Very low probability but high consequence events, such as catastrophes are difficult to fully anticipate and account for in models. Mangel points this out when he states that even well-managed systems can still 'crash'. His point strengthens the case for using uncertainty modelling methods such as those presented in our paper. One can decide how resistant to uncertainty a management plan needs to be and then model appropriate management solutions. Tools for making decisions under uncertainty will perform better than methods that ignore the probability of such crashes.

Finally, we wish to clarify a point in Mangel's response. In eqn 1, the parameter  $1/\beta$  is the mean dispersal distance (and not simply 'dispersal distance' as stated by Mangel). A log-normal probability distribution is constructed for  $\beta$  using the average and standard deviation of all the reciprocal mean dispersal distances for fishes in Kinlan & Gaines (2003). Mangel is correct that, in general, the average of the reciprocal of a distribution is not the reciprocal of the average of the distribution. However, we did not present the 'average' of the mean dispersal distance (which from Kinlan & Gaines 2003, is 112 km and not 22 km as Mangel calculates). Rather, we simply presented the mean dispersal distance that corresponds to the value  $\beta = 0.05$  or  $1/\beta$ , because that is how beta is defined.

Although the treatment of uncertainty can seem daunting to incorporate into conservation planning, people have long accepted it in many aspects of their daily lives. We fly in aeroplanes, we drive across bridges, and we manufacture and use chemicals. Engineers and risk assessors have figured out how to make these activities relatively safe for us despite the uncertainty inherent in such complex systems. We argue here that conservationists and resource managers can learn a lot from the techniques developed in these fields of research. The methods we present in our paper are not exhaustive. There is no single best tool for dealing with uncertainty – the best choice will depend on the management context and the quality and quantity of data available. Most importantly, such tools need to be integrated into management and conservation planning if we are to have any hope of making effective decisions.

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