An AEDA *info sheet*

Accounting for uncertainty in designing marine reserves

Better decisions are made when uncertainty is explicitly acknowledged and incorporated into your models.

Ecosystems are highly complex systems that defy prediction with certainty. Managing and conserving these systems in the face of this uncertainty is a daunting challenge. And getting it wrong – applying inappropriate strategies and decisions – can have dire consequences including population crashes, ecosystem collapses and extinction.

So, how do you deal with uncertainty? The traditional method has been to collect ever more data in an effort to reduce that uncertainty. But data collection is expensive and time consuming. Decisions often need to be made in circumstances where great uncertainty still exists about the system. Indeed, it's impossible to remove all uncertainty when managing a complex system. Delaying action while we wait for more data is often worse than making a quick decision with uncertainty.

In recent years new approaches to dealing with uncertainty in conservation management have been examined. Rather than simply accepting the traditional route of reducing the amount of uncertainty, these new approaches explicitly acknowledge and incorporate uncertainty into decision making. New research suggests that by incorporating (rather than avoiding) uncertainty, you increase the chances of successfully achieving conservation and management goals, while expending fewer resources.


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A good example of the advantages of dealing with uncertainty (rather than ignoring it) can be seen in efforts to develop networks of marine reserves.

Marine conservation and marine resource management need to deal with uncertainty all the time and fisheries managers have a range of traditional tools to accommodate this uncertainty. The design of networks of marine reserves for conservation is just as challenged when it comes to decision making in the face of uncertainty (and decisions here effect fisheries as much as conserving marine species). To design a reserve network, one must choose the sizes of the reserves and the appropriate spacing between the reserves.

In general, size and spacing rules are guided by estimates of how far larvae disperse (connectivity between reserves) and the patterns of adult movements. In particular, larval dispersal is necessary to ensure sustainability of populations for both conservation (supplying populations inside reserves) and fisheries enhancement (supplying populations outside the reserves).

However, actual measurements of movement patterns and larval dispersal distances for most marine species remain elusive. And the interactions of these dispersal parameters with population and community dynamics and environmental variables are extremely complex.

For example, uncertainty in larval dispersal estimates arises from imperfect knowledge about how many larvae are actually produced, their behaviour and the great complexity and uncertainty in the oceanographic processes that affect larvae (eg, ocean currents, wind and weather, climate change). On top of these biological and physical sources of uncertainty, uncertainty also arises from simple measurement error.

Despite this uncertainty in dispersal patterns, reserve size and spacing rules have been developed based on point estimates of average dispersal distances or models that assume various forms of dispersal distance distributions.

Reducing uncertainty through data collection efforts comes at great cost. For example, effective traditional fisheries management requires annual expenditures of millions of dollars, weeks of boat-time, and months of laboratory and analysis time to parameterize harvest models for each species. Design rules for marine reserve networks rely on the vast resources spent trying to develop estimates of dispersal and movement patterns.

Such expenditures may be necessary and highly valuable, but if uncertainty analysis can provide reasonable and robust design criteria without these extreme expenditures, then they hold great promise for conservation and management efforts.

Analysing uncertainty is not a new field. It's an important part of decision theory and probabilistic risk assessment and has been applied in economics, management and engineering for many years. Now conservation biologists are exploring its use.

A group of conservation biologists (Halpern et al, 2006) recently compared a variety of approaches to modelling uncertainty and used them to provide concrete guidelines for the design of marine reserves, in particular the spacing of reserves. They evaluated the optimal distance between reserves given different assumptions about uncertainty in dispersal distance.

Their analysis came up with four key results. First, all four approaches explicitly allow one to quantify the effects of uncertainty on model results and the consequences for subsequent decisions made in the face of uncertainty. The ability to quantify the impact

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to take greater risks if such risk creates the potential for a larger pay-off; in other cases, stakeholders will demand that any action provide the greatest amount of certainty in results. However, under the precautionary principle these decisions should be based on worst-case scenarios. Increases in persistence probability pay the price of requiring greater certainty in key model parameters, and this tension is quantified in these uncertainty models.

Second, greater levels of uncertainty in dispersal distance decrease the optimal distance between reserves. This is not necessarily a surprising result – if one is uncertain about a species' dispersal distance, it makes sense to put reserves closer together to ensure connectivity – but it illustrates how assumptions about parameters can affect important reserve design decisions. Allowing for uncertainty in the parameters increases the likelihood of meeting appropriate management or conservation goals. Furthermore, as the importance of certainty about an outcome increases (not just the expected value of the outcome), there will be a tendency to choose smaller distances between reserves.


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Third, although the results from the models analysed by the researchers do not provide exact guidelines for optimal reserve spacing, they do give useful minimum and maximum values for distances between reserves that should be used to ensure population persistence. Given a best guess estimate of mean dispersal distances for fishes (of 20 km) but high levels of uncertainty about this value, interval analysis (one of the forms of uncertainty analysis being trialled) shows us that reserves need not be closer than 10 km and should not be greater than about 350 km apart. If greater certainty exists about possible values for dispersal distance, then this range of potential reserve spacing values could be reduced.

Finally, info-gap analysis (a form of uncertainty analysis that deals with severe uncertainty) provides a truly precautionary approach to management and conservation. If the goal is to design a reserve network with a success rate that is robust to uncertainty, info-gap analysis tells us that unless we are fairly certain about our estimate of dispersal distance, reserves should be spaced at approximately 25 km apart.

The trade-off between certainty in parameter values and the size of the range of possible spacing distances in their analysis show how these models can also be used to evaluate the potential costs and benefits of reducing uncertainty in parameters. Data gathering to refine parameter estimates can be hugely expensive and time-consuming, and in some cases may not be possible. When there are differences in model results arising from different levels of certainty then the trade-off between data gathering and social tolerance for precautionary approaches will need to be explicitly weighed. Management can more confidently proceed in the face of uncertainty when the different uncertainty models provide similar reserve spacing rules.

Current guidelines for reserve spacing rules, based on estimates of average dispersal distances for marine organisms (using traditional techniques that seek to reduce uncertainty rather than explicitly acknowledge it), range from 10-20 km to 10–100 km for invertebrates and 50–200 km for fish. It is encouraging that the results of the analysis based on modelling uncertainty generate fairly similar guidelines.

However, by explicitly including uncertainty in the analysis you gain two critical improvements over more traditional approaches. By acknowledging and modelling uncertainty in parameter estimates, we have provided an explicit tool for describing and explaining to stakeholder groups the realities of the state of scientific understanding and the consequences of the uncertainty inherent in that understanding.

More importantly, the uncertainty modelling provides a mechanism for stakeholder groups to quantitatively evaluate acceptable levels of risk and then make informed decisions about reserve network designs based on those evaluations.

By acknowledging and quantifying the consequences of inherent uncertainty in our estimates of biological processes, rather than avoiding treatments of uncertainty, we should be able to manage and conserve more effectively the marine resources we want to use and protect.

Further reading

The ideas presented in this AEDA info sheet are based on the paper:

Halpern BS, Regan HM, Possingham HP and McCarthy MA (2006). Accounting for uncertainty in marine reserve design *Ecology Letters*, (2006) 9: 2–11.

In cases of severe uncertainty

In cases where a decision is required in conditions of severe uncertainty it's possible to use a technique known as info-gap analysis. For example suppose you wanted to evaluate the optimal spacing between reserves but you only have a best guess for the dispersal distance of the species you want to conserve and this best guess is highly uncertain by an unknown amount.

Info-gap theory approaches uncertainty analysis from the opposite direction as probabilistic methods. Rather than specifying the extent of uncertainty in parameters at the outset, info-gap theory takes the position that the best management strategy is the one that gives us an outcome that is acceptable under the greatest level of unfavourable uncertainty. That is, we choose a strategy that maximises the reliability of an adequate outcome.

Yakov Ben-Haim, one of the AEDA chief investigators based in Israel, is the inventor of Info-gap theory and has helped many AEDA members to understand and use this novel concept.