6.2.2 Fuzzy logic expert systems

The ability to classify or mathematically calculate ecological impacts in the marine environment hinges on the quality and quantity of available data. As mentioned in earlier sections, acquiring lots of robust data in the marine environment is costly and time-consuming. Fuzzy set theory, developed by Zadah (1965), provides a way of processing imprecise information and incorporating expert knowledge into a classification scheme. Fuzzy logic takes variables for which there is only 'expert' knowledge, or limited quantitative information, and allows the setting of fuzzy thresholds or boundaries between true or false rules. Conventional Boolean sets classify variables as either true or false; fuzzy logic classifies variables through a graduation of membership (Salski 1992, Silvert 1997).

Fuzzy set theory classifies variables according to their fuzzy membership functions. For example, Figure 5 from Cheung at al (2004) illustrates the output fuzzy sets for a single life history characteristic (age at first maturity) in their analysis of intrinsic vulnerability of seamount fishes to fishing. Using known relationships between age at first maturity and intrinsic vulnerability the authors transformed this attribute into a linguistic category. A fish at age 4 years, for example, has 0.5 membership in both medium and high intrinsic vulnerability categories. A fish at age 5.5 years has 0.3 membership in the high category and 0.7 in the very high category. At age 7 years or greater a fish has 1 (100%) membership in the very high intrinsic vulnerability category. These membership functions need to be determined by the available 'expert' knowledge using published data or data collated, specifically for the purpose, in an appropriate database such as SEAMOUNT (v2).

To create a fuzzy logic model a number of stages have to be followed. First, it is necessary to determine the model structure, the input and output variables, and the linguistics terms to be used, i.e., high, moderate, low risk. Then it is important to formulate the knowledge base; that is, where will the data come from; what expert knowledge is available; and which publications and databases can be used to inform the expert decision making. Every variable in the database then needs to be weighted or ranked in order of importance to the risk assessment, and fuzzy sets for every variable need to be defined, as in Figure 5. Next the fuzzy logic processing methods to be used are chosen, and once processing begins the model will need to be calibrated (tweak fuzzy sets) and then finally validated (Cheung et al. 2004).

Fuzzy logic processing methods generally follow the IF-THEN form. That is, IF A THEN B, where A is the premise and B the conclusion which may lead to other rules (Cheung et al. 2004). For example, using a variable from SEAMOUNT (v2) we might say;

IF *depth at base* = < 600 m THEN Risk is **High**

IF *depth at base* = 601–1200 m THEN Risk is **Moderate**

IF *depth at base* = > 1201 m THEN Risk is **Low**

More variables or rules are added during the processing to produce a range of conclusions, and ultimately a single point output for all rules, such as HIGH RISK. For example;

IF *depth at base* = < 600 m, AND *structural species* = present, AND *distance to shelf* = < 100 km, THEN Risk is **HIGH.**

While some degree of subjectivity is unavoidable in fuzzy set theory, the resulting outputs, be they linguistic or numerical, are calculated from the predetermined memberships in the fuzzy sets and the weighting assigned to each variable (see Cheung et al. (2004) for details of mathematical functions).

The advantages of using a fuzzy logic expert system are: (1) the linguistic categories can be defined in whatever way is most suitable, (2) it allows incorporation of information from a wide range of sources, (3) the predictive ability of the system can be increased all the time, (4) it can work for variables with different data availability, (5) it can adapt to new information from either qualitative expert knowledge or quantitative studies, and (6) once the data are compiled in a central database, various interpretive reports can be generated for difference purposes. The disadvantages of fuzzy logic expert systems are: (1) it can be difficult to estimate or agree on membership functions where this relies on expert knowledge, and (2) there are many ways of interpreting fuzzy rules, combining the outputs of fuzzy rules, and defuzzifying the output.

6.2.3 Qualitative modelling

The dynamics of marine ecosystems are driven by a complex series of interactions, including those between species, between species and their environment, and human impacts on the marine environment. However, there is a lack of quantitative knowledge of the interactions between many of these components, and the complexity of the interactions makes the overall effect of one component on others unclear. This makes qualitative modelling techniques attractive for understanding complex marine ecosystems, and potentially a means by which to assess the risk that a disturbance such as fishing has for habitats, communities, and species.

Food webs are one example of a qualitative modelling technique used in ecological research (Whipple et al. 2000). One way to represent a food web is as a signed community matrix with entries of (-, 0, +) representing the signs of species interactions. This type of representation emphasises the structure of interactions, instead of the often unknown quantitative values of interactions. Levins (1974) initiated a qualitative modelling technique known as loop analysis for analysing the stability of communities represented by signed community matrices, and for predicting the direction of changes in abundance of species to perturbations to the community. However, for large matrices (more than five species) or highly connected communities loop analysis techniques can be cumbersome and the results difficult to interpret. Loop analysis has been reformulated in terms of matrix algebra, and the interpretation of the results simplified with additional techniques (Dambacher et al. 2002, 2003a, 2003b).

A simple plankton community model is used here to illustrate the qualitative analyses techniques involved (Stone 1990, Dambacher et al. 2002). The signed digraph representing the food web and interactions for this community is show in Figure 6. Table 4 shows the associated signed community matrix with positive interactions represented by 1, negative interactions by -1, and neutral or ambiguous interactions by 0. From the signed community matrix the so-called adjoint matrix and weighted predictions matrix can be calculated, these two additional matrices being the key to a qualitative understanding of the community.

The adjoint matrix gives the predicted direction of response of quantities to sustained positive changes in other quantities (Table 5). The entries are the totals of all feedback cycles that led from one quantity to another, taking into account their sign. Entries can be negative, but in the plankton model none are. Entries of zero can occur when there an equal number of positive and negative feedback cycles going from one quantity to another, in which case the direction of a response will depend strongly on the actual value of interactions. This is the case with the response of zooplankton, phytoplankton, and nutrients to an increase in the abundance of bacteria. In contrast, an increase in the abundance of nutrients is predicted to give an increase in all other quantities.

The weighted predictions matrix has entries that are between 0 and 1 (Table 6). It measures the extent to which the predictions from the adjoint matrix are determinate: a value close to zero indicates that the predicted direction of change is very dependent on the quantitative value of interactions, while a value of one indicates that the predicted direction of change is independent of the quantitative value of interactions. Simulation studies indicate that entries that are greater than or equal to 0.5 give about 90% probability of obtaining the correct direction of change. For the plankton model example, most of the entries are greater than or equal to 0.5. In particular, the responses to a nutrient increase are positive, independent of the quantitative value of interactions. In ecological systems it is rare that actual interaction values between community members or ecosystem components are known, and in some instances they are exceedingly difficult to measure (Dambacher et al. 2003a). The composition or structure, however, may be well known and can be encompassed by a qualitative approach, and thus all that is needed is an understanding of the direction of interactions between ecosystem components.

Qualitative modelling is not an end in itself; rather it can use imprecise information to generate testable hypotheses about ecosystem responses to disturbance. In other words, qualitative modelling should be seen as a precursor to environmental risk assessment methods, highlighting the essential model components, the direction of their interactions, and the strengths or weaknesses of supporting data (Dambacher et al. 2003a, Ramsey & Veltman 2005). The advantages of qualitative modelling are: (1) that quantitative values need not be known, (2) biological groupings can be specific (the coral species *Solenosmilia variabilis*) or general (corals), and (3) and the model can incorporate non-biological variables, such as fishing pressure, or management decisions. The disadvantages are that: (1) the model predicts only the direction of changes, not the magnitude, and (2) the analysis assumes the community starts in an equilibrium state to which a perturbation is applied.

6.2.4 Sensitivity model specific to seabed habitat and fishing

Hiddink et al. (2007) have produced a novel method that models sensitivity of seabed habitat to disturbance by bottom trawling. They term the component concepts of risk resistance and resilience, which are synonymous with the previously discussed terms vulnerability and recoverability. The method relies upon information for the recovery time of production or biomass of benthic invertebrate communities which is predicted using a size-based model (Duplisea et al. 2002) that incorporates the effect of natural disturbance (see related work by Hiddink et al. 2006a, 2006b, 2006c). The method has been applied to data from the North Sea (at a scale of 9 km^2) and the measures of sensitivity have been mapped to provide environmental managers with what would appear to be a very robust tool with which to assess the risk of the adverse ecological effects of fishing. The method allows managers to "predict the implications of changing patterns of human impact on seabed habitats when establishing spatial management plans" (Hiddink et al. 2007). The authors claim that their method can be readily developed and applied to other situations and areas.

The advantages of this method are: (1) it is a quantitative and objective technique, not reliant on qualitative scoring by 'expert' opinion, (2) the model has been validated, (3) results can be used to make quantitative predictions of the effects of different management scenarios for fishing, and (4) data for most of the model parameters are available. The disadvantages are: (1) that not all data necessary for parameterising the model are currently collated at the scale of a seamount (e.g., benthic macroinvertebrate biomass – but some presumably available from bycatch records).

7. CONCLUSIONS

The addition of 41 new data fields makes the SEAMOUNT (v2) database a significant improvement on its predecessor. This development has been possible through the collaborative nature of the pooling of resources provided by the present MFish project and NIWA's Seamounts Programme. Although there is still a need to further advance the SEAMOUNT database, the potential utility of the database as a management tool is now considerably enhanced, in particular to support the type of ecological risk assessment envisioned by MFish's SMEEF. Data and information contained within the database can be used to provide indicators and measures of risk (some as suggested by this report) to habitats, communities, and species potentially threatened by fishing activities on seamounts.

A number of methods available for the task of risk assessment were reviewed as part of this project, and each was shown to have particular advantages and disadvantages, with arguably no one method emerging as a 'clear winner'. Overall, it is thought worthwhile to continue the preliminary evaluation of these and other methods (particularly those of Hiddink et al. (2007), Campbell & Gallagher (2007), and the recently published CSIRO-AFMA report) before deciding on which particular ecological risk assessment method should be developed further for application to New Zealand seamount management.

8. RECOMMENDATIONS

SEAMOUNT database

- Add more data fields (e.g., benthic biomass estimates using bycatch data, seamount morphology derived from automated approach, threatened species, connectivity indices, dissolved oxygen) as part of existing research projects where possible or new projects if required.
- Improve interactive capability through, for example, inbuilt GIS web-map functionality.
- Enhance linkage with other databases under NIWA's marine databases initiatives (including direct access to species occurrence data for seamounts).
- Determine a strategy for ensuring that the database is maintained in the long term and regularly updated.
- Develop a new project to implement the above four recommendations.

Ecological Risk Assessment method

- Hold a workshop to further explore the usefulness of the proposed indicators/measures of risk and how to best progress the preliminary development of an appropriate ecological risk assessment method for seamounts. Such an exploration, when attempting to determine which particular indicators/measures and method should be adopted, will need to be fully aware of the sorts of data currently available in the SEAMOUNT (v2) database (and likely to be available), and guide which sorts of data could be added without too much additional effort (e.g., benthic biomass). This workshop should involve governmental and industry stakeholders, as well as scientists from a range of disciplines and countries to evaluate different approaches.

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