NAMMCO

WORKSHOP REPORT

MODELLING MARINE MAMMAL - FISHERIES INTERACTIONS IN THE NORTH ATLANTIC

Reykjavik, 13 - 15 September, 2002

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1. OPENING REMARKS

Chairman Lars Walløe welcomed the members (Appendix 1) to the Workshop, and summarised the background to the present Workshop.

A 1996 Working Group (NAMMCO 1998) looked at the feeding ecology of minke whales, harp and hooded seals and found that there were many uncertainties involved in estimating consumption by these species. It also considered the use of multi-species models to assess species interactions in the Barents Sea and Central North Atlantic. The Scientific Committee, based on the results from the Working Group, concluded that minke whales, harp seals and hooded seals in the North Atlantic might have substantial direct and/or indirect effects on commercial fish stocks.

In 1997, the Council requested the Scientific Committee to pay special attention to studies related to competition and the economic aspects of marine mammal-fisheries interactions. The Scientific Committee, in response, convened a Working Group on the Economic Aspects of Marine Mammal - Fisheries Interactions (NAMMCO 1999). This Working Group considered bio-economic models of varying complexity and associated ecosystem models, and concluded that "many of the analyses were in a preliminary stage and should only be taken as first indications”. They further concluded that, despite the preliminary nature of the results, the emerging cost-benefit figures warranted serious consideration, as the overall costs to the fishing, whaling and sealing industries incurred by not whaling and/or not sealing could be quite considerable, and that the effects due to predation could be an important part of the overall picture.

At its 8th meeting in Oslo, September 1998, the NAMMCO Council tasked the Scientific Committee with providing advice on the following:

i) to identify the most important sources of uncertainty and gaps in knowledge with respect to the economic evaluation of harvesting marine mammals in different areas;
ii) to advise on research required to fill such gaps, both in terms of refinement of ecological and economic models, and collection of basic biological and economic data required as inputs for the models,
iii) to discuss specific areas where the present state of knowledge may allow quantification of the economic aspects of marine mammal-fisheries interaction;
    a) what could be the economic consequences of a total stop in harp seal exploitation, versus different levels of continued sustainable harvest?
    b) what could be the economic consequences of different levels of sustainable harvest vs. no exploitation of minke whales?

The Working Group on the Economic Aspects of Marine Mammal - Fisheries Interactions met in February 2000 to consider parts i) and ii) of the request. One of the conclusions of the Working Group was that significant uncertainties remain in the calculation of consumption by marine mammals, and this uncertainty was the most important factor hindering the development of models linking consumption with fishery economics (NAMMCO 2001). Considering this conclusion, the Scientific Committee decided to convene a workshop to further investigate the methodological and analytical problems in estimating consumption by marine mammals. This workshop resulted in concrete recommendations to estimate consumption by North Atlantic marine mammals, and a list of research priorities to refine existing estimates (NAMMCO 2002).

The Scientific Committee views the next logical step in this process to be a review of how presently available ecosystem models can be adapted for quantifying marine mammal - fishery interactions. Several different candidate models have so far been identified: the Icelandic BORMICON, the Norwegian MULTSPEC and Scenario Barents Sea, and the ECOPATH/ECOSIM model. The properties of different models will be discussed and compared, as well as the desired spatial and temporal resolutions. The Workshop is tasked with choosing a preferred modelling approach for analysing the ecological role of minke whales, harp and hooded seals, and other marine mammal species in the North Atlantic, identifying required input data and its precision, and recommending a process for further development of the model. Lack of knowledge of important input data will also be identified. An important consideration will be predator choice of prey given a range of available prey and prey densities. The Chairman emphasised that the Working Group should not expect to review results or make quantitative predictions at this meeting, but should rather focus on methodological problems.

2. ADOPTION OF AGENDA

The Draft Agenda (Appendix 2) was adopted with minor changes.

3. APPOINTMENT OF RAPPORTEUR

Daniel Pike, Scientific Secretary of NAMMCO, was appointed as Rapporteur.

4. REVIEW OF AVAILABLE DOCUMENTS

Documents available to the Workshop are listed in Appendix 3.

5. PROGRESS AFTER THE 2001 NAMMCO WORKSHOP

Analysis of NASS-2001 data continued within the NAMMCO Scientific Committee Working Group on Abundance Estimates. Preliminary estimates have been calculated for fin, sperm and humpback whales. New abundance estimates on the most important species including minke whales will be finalised in 2003.

Haug reported on recent research carried out in Norway on harp and hooded seals and minke whales:

- Collections to continue the time series on minke whale diet and body condition performed during commercial whaling in the North Sea, Barents Sea and around Spitsbergen.
- A new abundance estimate (based on sightings surveys in 1996-2001) for Northeast Atlantic minke whales is now available.
- Ecological studies (diets, body condition) of harp and hooded seals in pack ice waters of the Greenland Sea in the period between moult and breeding (July-February) had been continued. Modelling of total consumption of the two Greenland Sea stocks, based on new data and experience from similar work in the Northwest Atlantic and in the Barents Sea, is in progress.
- Abundance of Greenland Sea harp seals were assessed using aerial strip transect methods to estimate the 2002 pup production.
- Assessment of Barents Sea harp seal predation on resources in open waters are in progress: aerial surveys to map the distribution of seals are performed simultaneous with ship borne surveys designed to estimate the abundance and distribution of capelin.
- Demographic and ecological (primarily body condition) data collected seals from taken in the commercial hunt.

Víkingsson reported on recent research in Iceland:

- Sampling of stomach content of hooded seals in Icelandic waters was continued in 2002.
- Laboratory analysis of material sampled from bycaught white-beaked dolphins off Iceland is nearly complete.

Mikkelsen reported on recent research in the Faroe Islands. In the Faroes a scientific sampling programme was initiated in 2001 on white-sided dolphins taken in the traditional hunt.

The Chairman and others present reported that the Scientific Committee of the International Whaling Commission had held a workshop on a similar theme in La Jolla, California in June 2002. It was planned that the report from that meeting should be available [in confidence, pending its submission to the IWC] for this workshop in order to avoid duplication of effort, however the report has not yet been completed. The Chairman summarised some of the results from the meeting for the group. A general conclusion from the meeting was that interactions between marine mammals are a topic worthy of quantitative scientific investigation. The workshop investigated several candidate models, including MULTSPEC and ECOPATH/ECOSIM.

6. INTRODUCTION TO MULTI-SPECIES MODELS

The Working Group considered descriptions of the range of available multi-species modelling tools. This includes two general classes of models typified by the Minimum Realistic Models (MRM) on the one hand and the ECOSIM/ECOPATH approach on the other. The MRM class includes MULTISPEC, BORMICON/GADGET and Scenario Barents Sea. These models share the characteristics of being system specific, modelling only a small component of the ecosystem for a specific purpose, and treating lower trophic levels and primary production as constant or varying stochastically. In contrast, ECOPATH/ECOSIM is an all-inclusive approach that incorporates lower trophic levels and primary production.

i. Minimum Realistic Models- Doug Butterworth

The concept of Minimum Realistic Models was first introduced in the context of evaluating the potential impact of a then expanding fur seal population on the important fishery for hake off the west coast of South Africa at a Benguela Ecology Programme Workshop on Seal-Fishery Biological Interactions held in Cape Town in 1991 (Butterworth and Harwood 1991). The implementation of the approach to this problem is detailed in Punt and Butterworth (1995).

The key feature of the MRM approach is that consideration is restricted to species considered likely to have important interactions with the species of interest, Cape hake in this instance. Thus, in addition to the impact of fisheries, the model included seals and a grouping representing large predatory fish. Together with the effects of cannibalism and inter-species predation for the 2 hake species, the model then accounted for over 90% of the natural mortality of hake. The different components of the model were described at the level of detail considered necessary to capture key aspects of the dynamics: thus fully age-structured models were used for the 2 hake species to capture cannibalism and inter-species predation effects accurately, whereas the grouping of other predatory fish was modelled in a lumped fashion by only 2 linked components of small and large fish.

The analysis was set within the simulation framework of a 20 year projection under a feedback control rule for setting TACs for the hake fishery, to ascertain whether possible increases in the sustainable yield of hake in response to a seal cull might actually be realised. The robustness of the results obtained was checked by repeating the simulations for variants of the underlying MRM that involved primarily consideration of alternative values for parameters whose magnitude was uncertain.

In this initial implementation of the approach, the work had proved complex and lengthy. This, however, was seen as a consequence of the complexities of age-structured modelling of hake cannibalism and inter-species predation in this instance, rather than necessarily a general feature of the approach.

Discussion

The Working Group noted that since the models of this type provide a partial view of the ecosystem, the cost of ignoring un-modelled, weak ecosystem links should be assessed. More research in this area is required, possibly using simulation studies involving both strong and weak ecosystem links.

The approach as applied to the Benguela ecosystem demonstrated the requirement for ecosystem-specific models. A generic approach could not have captured the unique dynamics of even this rather simple ecosystem model. Any model is likely to require a large amount of work to adapt it to a particular area. Generalised modelling approaches must be very flexible and have accessible, easily modifiable coding so they can be adapted to specific situations.

ii. MULTSPEC- Sigurd Tjelmeland

MULTSPEC, which was established at the National Institute of Marine Research in Bergen, is a general-purpose multi-species simulator for the Barents Sea. It was initially designed to be a tool for calculating the spawning biomass of capelin, but later interactions between fish and marine mammals were included. At present the species capelin, cod, herring, polar cod, minke whales and harp seals are modelled.

The original application could be handled fairly rigorously since the general features of the migration were known – the capelin has to cross the entire population of immature cod to spawn every year and since there is a survey on immature cod during February, yielding not only the geographical distribution of cod but also a large quantity of stomach samples of cod.

When marine mammals were added rather counter-intuitive results were obtained. There proved to be a larger gain in the cod fishery by removing the seal population from the model than by removing the whale population, even if the whales eat more cod. Also, decreasing the suitability of herring as food for cod had a larger effect on the yield from the fisheries than removing the marine mammals altogether. The reason for this lies with the cod-herring-capelin dynamics. In order to get the marine mammals – fish interactions right the fish-fish interactions must be right.

At present MULTSPEC is resting and there has not been active work on this model for several years due to lack of resources. An attractive alternative for a geographically structured simulator for the Barents Sea is to implement the GADGET model. In addition simpler models are needed, like the Scenario model developed at the Norwegian Computing Centre. In view of the scarcity of resources this model should preferably be cast into the GADGET code.

In addition to these general-purpose simulators or simulators tailored to the marine mammals – fish issue, it is interesting to include consumption by marine mammals in fish assessment models. At the IWC cetaceans – fish workshop in La Jolla this year an attempt was made to include predation of Norwegian spring spawning herring by minke whales in the assessment model SeaStar. In the short term predation of capelin by harp seal will be included into the assessment model for capelin – Bifrost – on an experimental basis.

Discussion

It was noted that a version of MULTSPEC was being adapted for use in the western Pacific ecosystem by Japan, but no information on this effort was provided to the workshop.

The idea of including marine mammal predation in traditional single species assessment models such as Bifrost was considered a useful avenue of research by the Working Group. This should improve the performance of these models if predation by marine mammals is a significant component of natural mortality. In addition it will have the added side effect of increasing the demand for effective modelling of marine mammal predation, thereby assisting in the development of the scenario models of most interest to this group.

The rationale for including marine mammals in models, in preference to other predators such as seabirds, was discussed. Nevertheless it was considered that marine mammals would be a more productive focus for modelling in the candidate areas because the magnitude of their consumption is much greater than that of seabirds (Barrett *et al.* 2002). In addition, more and better data are available for marine mammals than for seabirds in the regions of interest.

The use of marine mammal populations as indicators of general ecosystem health was discussed by the Working Group. For some species, such as harp seals, there is a large amount of historical data on abundance and productivity, which could be correlated with fishery assessment and possibly climatic data. It was noted that Russian scientists are pursuing this with harp seals, and that marine mammals are used as indicators in the Antarctic. However it was considered that in most cases it will be easier to monitor the ecosystem components of interest, such as fish stocks, directly, rather than relying on an indirect indicator such as marine mammals. There may be significant time lags in the response of population parameters to ecosystem change in long-lived marine mammals. In addition, adaptive prey switching may mask significant ecosystem changes, as has been noted for both harp seals and minke whales.

iii. Scenario Barents Sea- Tore Schweder

Scenario Barents Sea is a series of projects at the Norwegian Computing Center in Oslo with extensive help and advice from Institute of Marine Research in Bergen and Tromsø. The two first projects were carried out from 1993 to 1999, while a new project funded by the ministry of Fisheries will be carried out in the period 2002-2004. In this new project harp seals will be included in the model. The aim is study how various management strategies for sealing and whaling will affect the Norwegian fish-fisheries, on the basis of our current knowledge and data concerning the population dynamics of, and interaction between, harp seals, minke whales, cod, herring and capelin. Another aim is to identify holes in our knowledge, and pressing data needs.

The previous projects compared management strategies for cod and herring (Hagen *et al* 1998); studied direct and indirect effects of minke whale abundance on cod and herring fisheries (Schweder *et al* 2000a); studied the effects on these fisheries of re-tuning the IWC/RMP for minke whales (Schweder *et al* 1998); and also compared management strategies with respect to long term resource rent, harvest capacity, catch, and abundance of cod (Schweder *et al* 2000b).

When studying the interaction between management of marine mammals and fish, the model in the previous projects has 4 species: cod, capelin, herring and minke whales. The fish populations are age and length distributed, while the minke whale is age and sex distributed. The time step is one month, and there are two areas (The Barents Sea and parts of the Norwegian Sea). There is a food-web with minke whales as top predators, consuming herring, capelin and cod according to a non-linear consumption function in available prey abundance. The consumption function for minke whales is roughly estimated. The opportunistic minke whale may forage on plankton and other fish than cod, capelin or herring, and is modelled as having carrying capacity and demographic parameters independent of the status of the fish stocks in the model.

The fish-fisheries are managed by fixed VPA-based fishing mortalities (cod and herring) and CAPTOOL (capelin), while minke whaling is managed according to the Revised Management Procedure (RMP) of the IWC (Schweder *et al* 1998). The model is stochastic in fish recruitment and in survey indices for minke whales. The model is simulated over 100 year periods in a number of scenarios spanned by 9 experimental factors. The core of the experimental design is an orthogonal array with 27 points. The primary study variable is the tuning of the RMP, and the response variables are catches and stock sizes of cod, herring and minke whale. The responses are taken as yearly means over the last 90 years of the period.

When the tuning of the RMP is changed from the current level of targeting the final stock at 72% of carrying capacity to 60%, the annual catch of whales increases with some 300 animals, while the annual catch of cod increases with some 0.1 million tons on the average. For herring, no clear main effect was found on catch or mortality rate. The catch of cod is estimated to increase in annual mean with some 6 tons when the whale stock is reduced with one animal. Schweder *et al* (2000b) found further that minke whale abundance affects the cod fishery in a similar linear fashion over a wide range of minke whale abundance. The results concerning the effects on the cod and herring fisheries must be taken as tentative since the ecosystem model used could be improved, and so could the strategies for managing the fisheries.

Discussion
The Working Group noted that the lack of data on some aspects of the model, particularly the response of predators to prey availability, had led the modellers to use plausible ranges rather than estimated values for some parameters in the model. While this was considered to be acceptable in a scenario testing model such as this, the sensitivity of the model to these parameters needs to be thoroughly assessed. Also, the lack of data on these parameters should be used to identify research priorities to fill in the gaps in knowledge.

Fishers are assumed to tailor their catches to quota decisions in some of the versions of this model, and no "economic behaviour" of fishers is included. Economic behaviour is, however included in one version of the model. Although outside the scope of fish-marine mammal interaction, it was found of considerable interest that Schweder *et al* (2000b) found that quota capping could produce substantial gains in the economic performance of the fishery, accompanied by a strengthening of the stock.

The fact that minke whales and harp seals were included as exogenous components of the model, so that their population parameters were not affected by changes in prey availability, was considered problematic by some members of the Working Group. Changes in harp seal condition, productivity and migration patterns have been associated with the collapse of the capelin stock in the Barents Sea in the 1980s, which apparently resulted in the "seal invasions" of the Norwegian coast. While it was considered that there is evidence to show that there are responses in seal fecundity and survival rates in response to food availability, there are insufficient data to model these responses at present, and they could be included in the model only with very great uncertainty. No such responses have been demonstrated for minke whales. Nevertheless the Working Group concurred that inclusion of endogenous responses to prey availability where such responses have been demonstrated would make the model more realistic.

The model is incomplete and does not include all the major predators of cod, herring and capelin, or even all marine mammal predators. If minke whale predation is reduced, it is possible that other predators, such as dolphins, killer whales or seals, may respond by increasing their abundance and predation pressure on these species. Therefore it was considered important that the main top predators are included in simulation models such as this. This will be difficult because the predators will have to be included as endogenous components that respond to competition by other predators. The functional relationships to model these responses are simply not available for most species, and certainly not for dolphins for which very little information is available. This should be considered a caveat in the use of models in which the top trophic levels are not completely specified. To include harp seals would help. But, if harp seals are exogeneous to the fish system, a reduction in minke whales will not allow harp seals to respond to the accompanying availability of food. It is therefore good reasons to make the harp seal an endogeneous component in the model. Schweder responded that attempts would be made to collect the information necessary to model the response of harp seals on fish abundance, and that the aim is to complete the model in this respect. Whether this could be done in the project Scenario C is however uncertain.

The linearity of the response of cod and herring catch over a wide range of minke whale abundance was considered surprising by the Working Group. Further it was originally thought that the removal of herring by minke whales would improve the survival of juvenile capelin, thereby enhancing the productivity of the cod stock, however this effect was not observed in the simulations. However the observed response is heavily dependent on the functional response to prey availability by minke whales, and data on this are poor. The meeting recommended that the sensitivity of model output to different assumptions for the form of functional response should be investigated.

Scenario – GADGET perspective

The new scenario project aims at updating the existing scenario model for the Barents Sea and the Norwegian Sea with improved predation structure and population structure. The project has limited funding, and will not accomplish much more than putting together the currently available data and knowledge in the existing framework, and to carry out simulation experiments.

The long term goal however is to transport the various components of the model to the system GADGET, and to build the model further in this system, at least when the GADGET allows the Scenario model to be used as a testbed (operating model) for management procedures. This will have a number of advantages. Some of these are:

- GADGET is likely to be better documented than the Scenario program and is expected to be better maintained and improved.
- With a general and openly available system tailored to fisheries the Scenario model is likely to be more transparent when implemented in GADGET than in the present C-code.
- In the GADGET system a data warehouse is available. This enables unified and easy access to fisheries data at appropriate levels of aggregation, which facilitates future updating of predation functions and other aspects of the model.
- Future data might allow migration patterns to be estimated for the various stocks. Implemented in GADGET, the Scenario model might model the spatial overlap explicitly.
- GADGET is general, and does not set limits to the number of components. In a GADGET implementation stocks like killer whale or shrimp might more easily be included.

For the future development of the Scenario model, parts of the model could be run over the Internet. This would enable models of subsystems to reside in their home institutions, and be improved and updated there.

iv. BORMICON/GADGET- Gunnar Stefansson

The first data-driven multi-species models to be applied to fisheries data, such as MSVPA[1], did not include any statistical techniques but used ad-hoc methods for estimating parameters. Further, since these models only included predation mortality but not the effects of consumption on the growth of the predators, they had some serious shortcomings in terms of applications to Arcto-boreal systems given the highly variable growth in these systems, sometimes attributed to the lack of food items. Further, since there are no spatial features in MSVPA, it is at best difficult to account for highly variable spatial overlap of predators and their prey.

The first such model to be applied to Arcto-boreal systems, MULTSPEC, addressed some of these shortcoming, being a spatially explicit model. MULTSPEC also applied statistical estimation methods through the use of likelihood functions, albeit in a rather limited sense. MULTSPEC was also fairly specific in terms of what were prey and predators, making additions and model changes somewhat difficult.

When initially developing models for Icelandic waters, a decision was made to address all of these issues at the design stage. The first model, BORMICON (A BOReal MIgration and CONsumption model) was a multi-species, spatially disaggregated model which took into account growth as a function of consumption and allow the user to specify their preferred likelihood functions. A deliberate design issue was to be able to accommodate quite different components of population

[1] MSVPA is a multispecies extension of Virtual Population Analysis (VPA). VPA involves estimation of annual recruitments to a fish population by summing fishery catches-at-age up each cohort while at the same time making allowance for losses to natural mortality (M) each year. In standard VPA, M is customarily taken to have a constant value, independent of year and age. Multi-species VPA performs this estimation simultaneously for a number of species. The important extension to standard VPA is that consumption by a predator species is explicitly included in the computation of natural mortality losses for the corresponding year and age for the prey species in question, so that M for each species becomes both age- and year- dependent. These computations are based on diet composition studies.

dynamics models and different likelihoods for different species and data sets, thus allowing for varying levels of knowledge and different data collection schemes. Thus a fairly generic environment for model development was designed, rather than a single model. This environment is a flexible platform for models (or model components) of biological processes. Although a model implemented in GADGET can be quite complex, this is inevitable when testing complex hypotheses. It is simply not possible to evaluate the importance of temporal - spatial overlap without explicitly taking these into account.

BORMICON was subsequently used as a basis for FLEXIBEST for assessments of NE Arctic cod. The various developments have been co-ordinated as a European project with a current program (2000 - 2003) which includes models such as the initial FLEXIBEST and BORMICON as special implementations. It is important to note that any specific growth models, suitability functions etc are intended to be modules, with alternative formulations easily added.

Within the European framework, the goals were to: Obtain a model/tool which describes the most important features of the system as it relates to fish; Understand the models/limitations; Understand the underlying multispecies dynamics; but not at this stage to obtain an assessment toolbox.

The current program, GADGET (Globally Applicable Area-Disaggregated Generic Ecosystem Evaluation Tool), is a fully parametric forward simulation model (and can therefore in principle be run without any data). A simulation results in population trends by species, size class, age group, area and time step. These trends can subsequently be compared to data using appropriate likelihood functions, eventually maximising the likelihood functions to obtain parameter estimates.

Consumption within GADGET is modelled using suitability functions and mortality can be either due to predation, other natural causes or fishing.

Growth is implemented via movement up through length classes and can depend on consumption, with several growth update mechanisms already available.

Migration is implemented through movement matrices. In principle these can vary by time step, but in typical case studies they are assumed to be fixed in time.

The species life cycle has not been closed within GADGET at present so spawning, as currently implemented only results in weight loss. It is foreseen that during the coming year first models with a closed life cycle will be tested with larval drift of fish implemented through exogenous hydrography-driven movement matrices.

The model is completely symmetric across species and areas so that e.g. a predator's behaviour is defined only through associated data sets and parameterisation.

Parameters are estimated using maximum likelihood. These likelihood functions are sometimes quite difficult and can be multi-modal due to several reasons, requiring global minimisation algorithms for initial estimation, followed by local minimisers which zoom in on the minimum. Given that individual simulations can require considerable computing power, a parallel minimisation algorithm has been designed.

A number of likelihood functions have thus been implemented but recent work indicates that many common data sets defy the most common statistical assumptions. It has also been seen that model "stiffness" implies that too much weight given to a data source (i.e. incorrect likelihood function) can lead to widely varying population trends, which is in stark contrast to well-known results in linear statistical models where incorrect variance assumptions tend to be of minor significance.

Since GADGET is a parametric model, it can in principle run without data. For data-poor species, highly detailed models which require large numbers of parameters can not be reasonably implemented and the modeller is forced to use simpler models with fewer parameters. For some marine species highly detailed data are available and these can then be used to fine-tune highly detailed models.

Given the data requirements, it is obvious that if data is entered into GADGET data files by hand or using manual extractions from raw data bases, revisions of spatial aggregations or length groupings will require considerable revisions of the data files. For this reason a data warehouse has been defined in such a way that it consists of mildly aggregated data in standardized tables. Extraction routines for assessment purposes have been written and extraction routines for GADGET are under development.

Current case studies within the European framework include Icelandic waters, the Celtic Sea and North Sea herring. For each of these areas a multi-species model is being implemented using GADGET with data extracted from standardised tables in each area.

Current implementations include several species within Icelandic waters (single species, single area up through 3-species in 10 areas), Barents Sea cod. In spite of known problems, the program is currently used for assessments in several case where no alternatives exist to account for known important processes within the system.

Future work includes obtaining reliable estimates of uncertainty, implementations of tagged sub-populations, development of new likelihood functions and closing the life cycle. The most promising approach to estimating uncertainty appears to be bootstrapping but considerable work is needed in this area, given the correlated nature of the measurements.

Discussion

The Working Group was impressed with the scope and ambition of this project in attempting to establish a framework for ecosystem models of various levels of complexity. When put to use, the GADGET system will provide a strong and unified platform for data handling, scenario modelling and simulation, and model fitting. Such a unified platform is certainly welcome, and so is the information technology that is put together in GADGET. However, even with good information technology as GADGET, much work remains for the particular modelling exercises. Scenario- and assessment models are necessarily case specific, and all the specifics needs to be worked out in each particular case.

It was noted that marine mammals have not been included in any of the GADGET case studies to date. Earlier attempts to include cetaceans in multi-species modelling in Icelandic waters (Stefansson *et al*. 1997) have shown that more data on diet of minke whales is required for the Icelandic area.

The simultaneous maximisation of likelihood for up to hundreds of parameters in non-linear models is problematic due to local maxima and other difficulties. To allow the parameters of the model to be fitted simultaneously to the collection of relevant but fragmented data is highly desirable, but very taxing. In GADGET, global maximisation is carried out, which was applauded. However, with a highly non-Gaussian likelihood, the information matrix is not particularly informative of the statistical properties of parameter estimates. One intermediate course would be to fit parts of the model to relevant parts of the data, and then to reserve only a limited number of parameters for the final simultaneous fitting. The other parameters would then be kept constant at their partial estimates. In the discussion, it was pointed out that when a sound likelihood function is available, the scene is set for valid parametric bootstrapping. Statistical measures of uncertainty in conclusions are thus much better obtained by bootstrapping than by calculating the Hessian at the computed maximum.

The scope for a Bayesian approach to quantifying the uncertainty in conclusion was also mentioned. This might be possible through simulation when well argued prior distributions are available.

v. ECOPATH/ECOSIM

ECOPATH is an equilibrium approach to multi-species modelling. Mass balance equations are used, essentially relating production by some species to predation by others under the assumption that the system is in a steady-state. Unlike the models discussed above, ECOPATH also considers the lower trophic components of the ecosystem e.g. plankton. ECOSIM builds upon this approach, but drops the equilibrium assumption so that the system is modelled by a set of coupled differential equations. Attempts had been made to invite a scientist experienced with applications of ECOPATH and ECOSIM to make a presentation to the meeting, but unfortunately without success.

Discussion

Potentially ECOSIM could provide a basis to provide advice on marine mammal-fisheries interactions. An advantage of the package is the structured framework it provides to setting out species-specific inputs required for multi-species modelling. Potential disadvantages discussed included the inbuilt functional forms for species interactions, and simplified treatment of age-structure, that may not be appropriate for the particular cases to be considered. Another problem is the large number of parameter values that need to be specified; some of these may have an appreciable impact on outputs, and the default suggestions provided by the package may not be the most appropriate in all circumstances. Furthermore, ECOSIM is at the other end of the spectrum of possible models compared to the single species approaches currently used as the basis for management advice, in the sense that it attempts to model all elements of the ecosystem. A less expansive approach, building from single-species experience and without immediately attempting to incorporate phyto- and zooplankton dynamics, might be more appropriate as an initial advance from current practice.

7. PREY SELECTION PROCESSES

Prey selection by minke whales in the Barents Sea – Ulf Lindstrøm

To elucidate the prey selection function of minke whales, Norwegian Institute of Fisheries and Aquaculture performed studies of minke whale foraging dynamics in selected areas in the southern Barents Sea in 1998 and 1999. Stomach contents were sampled onboard commercial whaling vessels whereas the resource availability was assessed using standard acoustic surveys by research vessels. Three different approaches were applied to make inferences about minke whale selectivity:

1. Chesson’s selectivity index,
2. Multivariate statistics
3. Empirical Bayesian statistics.

The first approach involves use of the bootstrap, i.e., the index was calculated for each prey type and then tests were carried out to look for deviations from random feeding. This was done by calculating approximate 95% confidence intervals for the expected index value for each prey. These were compared with the expected index value on the assumption of random feeding. The prey availability was estimated by bootstrap sampling of assumed independent resource samples

The second approach involves constructing multivariate confidence bounds (ellipsoids) to delimit expected prey proportions in the diet and the environment and thereby reveal significant differences. For the diet analysis, the bootstrap was applied to obtain precision measures of the dietary prey proportions, whereas in the spatial analysis of prey densities, intrinsic geostatistics were applied; statistically homogenous conditions are assumed. Because whaling and resource sampling were not simultaneous, the whales may have experienced different resource availability than observed during the resource mapping. To account for this uncertainty, the variation between realisations of the prey density process was included in addition to the sampling uncertainty for each realisation.

The methods applied in the two previous approaches were based on extensive use of the bootstrap, but since use of the bootstrap is strongly dependent on a sufficient number of independent samples, a simplified binomial model was applied to the diet analysis with special emphasis on capelin. The expected proportion of capelin in the diet was estimated as the number of whale stomachs dominated by capelin divided by the total number of non-empty stomachs. For a given capelin proportion in the sea (q), the p-value can be found by a classical method. That is, the simulated distribution of capelin proportions in the sea, provided by the methodology in previous approach, was considered the *a priori* distribution for the unknown q. The appropriate p-value was the defined as the mean in the posterior distribution of p conditional on q

The prey selectivity of minke whales was analysed over various levels of spatial resolution, which turned out to be important considering the results from three consecutive resource surveys performed in one small-scale area. The spatial pattern may change rapidly, particularly with respect to pelagic shoaling fish such as capelin and herring.

It was concluded that there is an apparent advantage of multivariate over univariate comparisons of prey preference when strong prey correlations are involved in the diet and the environment. Accordingly, if the sample size is sufficiently large, the multivariate approach is recommended. On the other hand, with few whale samples the Bayesian statistical approach seems promising.

Discussion

Haug noted that large scale spatial and temporal correlations between prey abundance and minke whale diet have been observed. In years when strong year classes of juvenile herring area available, herring can dominate the diet in areas where the distribution of minke whales and juvenile herring overlap. The proportion of capelin in the diet also tracks capelin abundance to a large extent.

Studies of the type presented provide estimates of prey selectivity at the microscale. However, multi-species models require estimates of such consumption functions at the macroscale (the spatio-temporal scale of the strata adopted for the population dynamics modelling). Conversion of the results from microscale experiments on selectivity to yield macroscale estimates is not straightforward, as the results will depend on the spatio-temporal distributions of predators and their different prey species, and the former may alter in response to changes in the latter. In the short to medium term, the prey selectivity values needed for multi-species models will likely need to be based on the aggregated approach of regression analyses relating observed changes in annual average predator diet to varying prey abundances provided by assessments - hopefully such data will provide sufficient contrast to allow for reasonable estimates to be obtained by this approach. Nevertheless, detailed, smaller scale efforts should be continued to elucidate the mechanisms behind prey selectivity, and to allow the conversion approach to be applied in the longer term. It was noted that a potential problem with the aggregated approach was the non-random nature of the diet data, which is dependent on samples taken from the commercial hunt. There is evidence from sightings surveys and incidental observations that whales occur in areas where they are rarely hunted. While a randomised sampling program to obtain diet samples would be preferable, it was considered highly unlikely that this could be realised in the near term.

The available data on minke whale diet covers a limited seasonal window, and this could confound the estimation of consumption functions. Most diet data comes from commercial whaling in May and June, and there is almost no data from the rest of the year. In addition, catch locations from commercial whaling conducted after the 1950s show that the location of catches can vary substantially from year to year. In some years, catches were concentrated close to the Finnmark coast, while in other years whales were caught farther north and east in the Barents Sea. This reflects variation in the distribution of minke whales from year to year, which in turn may be due to changes in prey distribution. Since it is not possible to sample animals throughout the year on an annual basis, a basic assumption will have to be made that consumption patterns do not vary temporally or spatially, until this assumption can be tested.

Simulation of minke whale suitability with special emphasis on herring and capelin –Ulf Lindstrøm

The main objective of this preliminary simulation study is to understand how local and large-scale predator-prey processes are linked, and preferably come up with a “running average” estimate of the functional response.

The model will include a resource simulation model and a minke whale foraging model. The simulation of resource densities is performed by using intrinsic geostatistics, as described before, whereas a dynamic state variable model will be used to simulate the minke whale's foraging behaviour. The resource simulation model and ten resource simulations were presented at this meeting along with a simple random walk model.

Discussion

The Working Group noted that the simulation-based estimation of selection parameters should be a valuable if ambitious approach in this area. Using realistic simulated prey fields, the behaviour of simulated predators can be modified until the resulting simulated diet observations mimic those realised in the field under similar conditions. The resulting functions should be extendable to other areas and prey conditions within the range of the simulation testing.

It was noted however that there may be a need for greater complexity than that presently incorporated in the model. Suggestions included including a prey depletion function, such that predators deserted the food patch once density fell beyond a threshold level; inclusion of 3 dimensional foraging; modification of searching behaviour upon encountering a patch; incorporation of state variables such as stomach fullness; and incorporation of temporal change in the prey field. While this will introduce further complexity into the model the results should more realistically mimic observed behaviour.

Modelling diet choice and consumption functions – Tore Schweder

There is a rich economic literature on human choice- and consumer behaviour, and there is a wealth of experience in estimating models on both the individual level and on the aggregated level. The economic paradigm of rationality is that humans make their choices on the basis of utility maximisation within the options available in the situation, and under budget constraints. A weak form of this paradigm might also be appealing to the biologist when modelling animal behaviour on the micro level. One might therefore think that the economic and econometric literature on choice- and consumer behaviour provides guidance when predation, diet choice and foraging is to be modelled for fish and marine mammals (and also terrestrial species).

Ben-Akiva and Lerman (1985) give an introduction to the theory of discrete choice behaviour. To fix ideas, consider the following constructed adaption of this theory. A minke whale might feed on krill, herring, capelin, gadoids or other food. In this situation, it faces a choice set of 5 alternatives. Each food item is characterised by an (observable) attribute vector x, say of calory density, local abundance and patchiness. To each choice alternative, is associated a potential utility to the whale. This alternative-specific utility is modelled as $v(x)+r$, where r is a random component covering unobservable individual taste variation and other sources of random variation, and v transforms the vector of attributes to a scalar utility. The theory is then that the minke whale chooses that food item within the choice set that maximises the individual whale's utility. A popular specification is that the random components are independent over alternatives, and follow a Gumbel distribution. In this case, the probability that the whale chooses a particular food item follows the multinomial logit distribution. A consequence is that the popular axiom of independence of irrelevant alternatives (IIA) is satisfied. This means that everything else equal, the conditional probability P(capelin | herring or capelin) is the same whether krill, or gadoids are open options – and correspondingly, any other conditional choice probability is fixed regardless of which other options that are available.

In a further development, Dagsvik and Strøm (2002) draw on the psychophysical literature, and find theoretical support for specific functional forms for the function v transforming attributes to utilities. The logarithmic transform is a possible function. It leads to multinomial logistic choice models for which the logits are linear in log prey fattiness, log prey density, log prey patchiness etc.

The example with minke whale diet choice is meant to illustrate that this economic theory might have something to offer, rather than a solution to the very difficult problem of estimating diet choice and selectivity functions in minke whales.

Discussion

It was questioned whether the IIA assumption would indeed hold true for marine mammals. In a case where there are two prey items for which selectivity is the same, the relative selectivity for each will be lower if both are present because the predator will not distinguish between them. In response Schweder pointed out that with the same selectivity the two items would be considered to be the same under this scheme, and that classification of prey items would not necessarily by species. Two or more species could be grouped together if they are not distinguished by the predator.

There was some discussion over whether baleen whales in particular actually do select prey, or whether the observed apparent selection might be the result of applying 2 dimensional dynamics to a 3 dimensional distribution of predators and prey. Also, the range at which prey items can be distinguished might be quite short, which would make selection unlikely. However it was noted that the observed positive selectivity of minke whales for capelin was in some cases so extreme that it could not be a result of depth distribution, since the depth distribution of capelin and herring was similar. Also, the selection may not occur at a distance, but prey might be ingested and then rejected.

8. RECOMMENDED MODELLING APPROACH FOR NAMMCO

In reviewing the amount of multi-species modelling work and associated applications to management decisions that had been conducted world-wide over the past several years, the Working Group noted a much lower than expected activity in this area. This was considered surprising given the emphasis politicians and management authorities have placed on multi-species (ecosystem) approaches to the management of marine resources. While the principle of multi-species management seems to be widely accepted, the practical aspects of putting it into practice lag far behind the rhetoric. The Working Group emphasised that progress in this area will not be made unless significant additional resources are dedicated to it.

The Working Group identified the following desirable general features of a modelling approach that would be applicable to analysing marine mammal – fisheries interactions in the candidate areas of the North Atlantic:

- Flexibility of functions for prey selection that can be manipulated by the modeller;
- Flexibility of age structuring, from fully age structured to fully aggregated;
- Accessible source code and transparency of operation- the model must not be a "black box";
- Able to be tailored to the area and species of interest, rather than generic;
- Model interactions accounting for most of the natural mortality of the fish species of concern;
- Spatial and temporal resolution tailored to the target species, with flexibility for changing resolution.
- Uncertainty in data and model structure is reflected in the results.

Considering the data available or likely to become available in the foreseeable future, the Working Group favoured the approach of using a limited model that encompassed only the major species of interest, as opposed to an all-encompassing model where all or most species are included, as a basis for potential management advice in the short to medium term. This approach can be described as a Minimum Realistic-type model, as exemplified by Scenario Barents Sea, MULTSPEC and BORMICON. It was considered that the data demands of a more comprehensive model would be too great for the model to be sufficiently realistic and estimable that there was little likelihood of them ever being satisfied. This would necessitate more guesswork in the specification of such a model. Other components of the ecosystem that are not explicitly modelled, such as primary production or zooplankton, could be left as constant, allowed to vary randomly or linked to environmental covariates. While the output of such a model could not be expected to predict all aspects of future states of the ecosystem, they will be useful for testing management scenarios where the abundances of target species are manipulated.

Some members voiced the concern that the development of ecosystem models without sufficient data in some components would produce results that might be used by inappropriately by managers, who might not understand the level of uncertainty in the results even if it is specified. It was suggested that it would be better to wait until the required data is gathered before proceeding to ecosystem modelling. Other members noted that even models in which some components are parameterised with “plausible ranges” can be useful in determining the sensitivity of the model to variation in parameters, and thus in determining the most important gaps in knowledge. It was agreed that the two activities should proceed simultaneously: that is, the data gaps identified in previous workshops should be filled by dedicated studies, while modelling can proceed in candidate areas, even with partial data, as long as the uncertainty of the results is emphasised and integrated in the results. In this way, modelling approaches can be refined and the reliability of the results will improve as more data is gathered.

There was agreement that the continued development of the Scenario Barents Sea model should be a priority, with emphasis on incorporating the predation of harp seals in the model. The model would be improved by including harp seals and possibly minke whales as endogenous in the model in the sense that their life history parameters would affected by variation in food supply. However this would be subject to considerable uncertainty given the current lack of information on these effects. The Working Group also recommended that this model be transferred to the GADGET platform after the current round of development has been completed. This will facilitate interface with present single species assessment models, and enhance the transparency of the model and the possibilities for future development. It was noted that such a transfer will require additional resources that are not currently available.

In addition to the above the Working Group recommended the development of a second, more general North Atlantic "template" model based on the GADGET platform. This spatially homogeneous model would include species important in candidate applications to West and East Greenland, Iceland and the Barents and North Seas. However the abundance of these species would be varied between the areas according to available information. The quality of the available input data varies greatly between areas, and in cases where little information is available, plausible ranges would be used. It will be crucial to capture the full range of uncertainty in these ranges.

In areas where data is lacking, such as West Greenland, the main use of such a model will be to identify the sensitivities to variation in input parameters, and thus to assist in the setting of priorities for research. In Icelandic waters, where better data is available for fish but data on marine mammal diets and prey selection are scarce, such a model will serve the same purpose but also generate preliminary scenario results for management. For the relatively data-rich Barents Sea area, the model will augment the main Scenario Barents Sea modelling effort.

The Working Group recommended the establishment of a planning group to develop the specifications of the template model, should the project proceed. It was emphasised however that the development of such a model is not presently planned or budgeted, and will require additional resources to proceed.

To summarise, the Working Group settled on a two-pronged approach to modelling marine mammal – fisheries interactions in the candidate areas. The first approach will be the further development of the Scenario Barents Sea model, which is already proceeding but could be enhanced with additional funding. The second suggested approach is the development of a more generic, North Atlantic-wide template model based on the GADGET platform, including major fish and marine mammal species of interest from all the candidate areas. The model should be applied to areas that best suit the distribution of the candidate species, as well as available fisheries and marine mammal datasets. The model will initially serve mainly as a mode for sensitivity testing to determine the most profitable avenues for research. As more data becomes available, this model could be further developed into Minimal Realistic-type models for the candidate areas.

9. FUTURE WORK

i. Collection of input data

The Working Group reiterated the priorities for future research identified by the Scientific Committee of NAMMCO in 2001 with regard to refining the estimates of the consumption of marine mammals in the North Atlantic (NAMMCO 2002).

The functional nature of prey selection by marine mammals under varying levels of prey abundance and from mixtures of available prey was considered a further priority for further research. To derive these functions diet data must be collected in conjunction with resource surveys at appropriate temporal and spatial scales.

Migration by fish and marine mammals was considered to be one of the most important factors in modelling their interactions. A great deal of data is available for many of the major fish species, which could be analysed to develop migration models. For marine mammals, there is very little data and much more research is needed, possibly through continued satellite tagging studies.

Data warehouse

It was considered that the Data Warehouse facility offered by the GADGET platform would be an ideal platform for compiling data for future modelling efforts. The use of this facility was strongly encouraged.

Testbed

At present GADGET lacks the scenario aspect where the management process itself is modelled in prognostic simulations. Only when this option is available will it be possible to use an implement the Scenario mode for its original purpose: to compare management strategies and their related assessment machinery. Developments in this direction should be encouraged.

ii. Linkage to economic models

It was considered that discussion of the economic aspects of marine mammal-fisheries interactions would be premature until these interactions has been initially described and quantified. Once models are available that can predict the variation in target species in response to management measures, linkages to simple economic models that assess the economic consequences of the responses can be made. However it was cautioned that more complex economic models integrating the economic behaviour of fishers and markets under different conditions of resource abundance are themselves subject to great uncertainty and a subject outside the scope of the present Working Group.

10. RESEARCH NEEDS

The Working Group reiterated the research priorities identified by the NAMMCO Scientific Committee in 2001 (NAMMCO 2002). In particular the Working Group emphasised that additional information on harp seal diet and consumption in the Barents Sea is a priority to further the modelling work. In addition the Working Group identified the following priorities:

Prey selection

- theoretical and practical work on prey selection models
- development aggregated consumption functions
- migratory and spatial aspects of consumption models

Multi-species modelling

- Further work on the Scenario Barents Sea model
- Use GADGET as a framework to generate template models for candidate areas in the North Atlantic

11. ADOPTION OF REPORT

The report was approved at 18:40 on 15 September.

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APPENDIX 2

AGENDA

1. Opening remarks
2. Adoption of Agenda
3. Appointment of Rapporteur
4. Review of available documents
5. Progress after the 2001 NAMMCO Workshop
6. Introduction to multi-species models
    - i. Minimum Realistic models- Doug Butterworth
    - ii. MULTSPEC- Sigurd Tjelmeland
    - iii. Scenario Barents Sea- Tore Schweder
    - iv. BORMICON/GADGET- Gunnar Steffansson
    - v. ECOPATH/ECOSIM
7. Prey selection processes
8. Recommended modelling approach for NAMMCO
9. Future work
    - i. Collection of input data
    - ii. Linkage to economic models
10. Research needs
11. Adoption of report