DATA REQUIREMENTS OF MULTISPECIES, SPATIAL, AND ECOSYSTEM MODELS

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Abstract

Traditional biomass dynamics and age-structured models of a single species within a single spatial unit are being supplemented by models that incorporate fishing effort dynamics, multiple species, spatial heterogeneity, and trophic interactions. These extensions impose a demand for data far beyond that required for the simple single species models. Information on the levels of interaction at different ages between species and their response to changes in the physical and chemical environment must be provided. Movement within the spatial boundaries of the system, and a detailed understanding of the spatial distribution of recruitment are required if spatial heterogeneity is to be modelled. A sound understanding of the system to be modelled is fundamental to the selection of appropriate boundaries and of an appropriate resolution of space and time to be used within these more complex models.

Introduction

While traditional single species models remain the most frequently used tools of fisheries science, there is an increasing awareness that these models may be inadequate to deal with the complexity of the systems that they attempt to represent. A variety of extensions to the traditional models have been proposed. These cover models that incorporate the response of the fishing fleet to changing abundance of the exploited stock, models that reflect the spatial distribution of the fish stock and of the applied fishing effort, multispecies models, and models that represent the ecosystem (Figure 1).

The data needs of these various models differ according to the boundaries of the system represented by the model, the level of abstraction used within the model, and the aspect of the system that is modelled. Of necessity, in a general discussion of data needs, a broad approach must be taken; the specific details of the data required by a particular model must be determined by the form of the model, and the method of implementation used.

Single Species Models

When research is commenced on a fishery, traditional single species models are usually used to provide initial management advice. The data needs are well known (see, for example, Shepherd 1984), and collection and maintenance of such data becomes one of the key elements of the research programme that is initiated. Such data (Table 1) are also essential for each exploited fish stock for the more complex models, and some further elaboration will therefore be presented here.

The identification of the stock that is being exploited must be examined in order to determine whether the fished stock can be treated independently of neighbouring exploited populations of the same species. This may involve the collection and evaluation of taxonomic data, electrophoretic data, morphometric data, tagging data, analysis of chemical and biological (parasite) tracers, etc.

Of fundamental importance are the time series of catch, fishing effort, and abundance data that are collected. These form the basis of much of the modelling for the fishery. Although the fishery is treated as a single unit within the traditional single species models, data are often collected in a spatially disaggregated form. This provides the data needed when calculating average catch rate for the fishery to correct for the movement of the fishing fleet to areas of high stock abundance.

It is essential that both catches and landings are recorded, as the latter exclude discards that may experience fishery-induced mortality. Fish may be discarded as a consequence of management regulations (e.g. the return of fish with lengths below a minimum legal length), as a consequence of a vessel's limited capacity to handle or store the entire catch, or as a result of catch quotas or limited market demand (e.g. varying demand for redfish from the south eastern trawl fishery of Australia) and associated "high grading" of landings. Where quotas are involved, a variety of biases are likely to occur (Copes 1986), e.g. where the value of the catch is high, "leakage" may occur and recorded landings will under-report the true impact of fishing; "leakage" is defined here as the movement of landed catch through unofficial or unreported channels. Where data on the quantity of fish discarded are available, there is a need for accompanying studies to be undertaken to determine the survival rate of the discarded fish.

If the fishery utilises a variety of gears, data on catch and fishing effort should be disaggregated by the gear type used. Similarly, if different fishing fleets operate within the fishery, the data should be disaggregated by fleet; where the fish stock is shared with recreational fishers, and a significant portion of the catch is taken as recreational catch, information on the number of recreational fishers, gear used, duration of operations, and catch taken must also be obtained. However, where the recreational catch is relatively small, reliable commercial catch records are usually sufficient.

Accompanying the data on fishing effort, a time series of detailed data should be maintained that describes the vessel, number of crew, experience of skipper and crew, fish finding and navigational equipment, and fishing gear used. Major difficulties that exist for research into most fisheries are the changes in fishing efficiency (fishing power), the changes in gear type (selectivity), and the changes in fishing practice (tactics) that occur through time, i.e. factors affecting catchability. If effort data are to be relevant, they must be accompanied by these detailed records so that standardisation can be undertaken. These factors that affect the unit of effort should be regarded as measures of the "behaviour" of the fishing unit and studied with the same rigor as is usually applied to the behaviour of the fishes.

To avoid the difficulties of changing fishing power associated with recorded commercial or recreational fishing effort, standard research survey data can be substituted provided sufficient effort can be applied to produce a reliable measure of abundance. Such surveys allow the use of standard statistical methodology including, for example, stratified sampling (both spatial and temporal) and replication to achieve a known level of precision.

Not only are indices of the abundance of the exploited fish required, but it is also useful to obtain time series of abundance of mature and spawning fish, of new recruits to the fishery, and of pre-recruit juveniles. Egg and larval surveys may assist in determining the extent and magnitude of the parental stock, particularly in the case of pelagic schooling species (Fletcher *et al.* 1992), and may provide useful indices in models that attempt to link the life stages or incorporate an explicit model of the stock-recruitment relationship.

Accompanying the information on catches, biological time series data are also required on the sex, size, and age composition of the catch, discarded fish, and landings. Standard information must also be available on the relationship between body weight and length, length and weight at age (growth), and fecundity at age. An estimate of the instantaneous rate of natural mortality is needed, and an understanding of the selectivity and efficiency of the fishing gear is required.

It is important to note that the recorded data must capture sufficient contrast in levels of exploitation experienced by the fishery if they are to have great informational content and be useful in model development. Data from the early years of exploitation of a fish stock are therefore frequently of great value when the data are analysed.

Time Varying Parameters

Fundamental to these single species models is the assumption that the response of the fish stock to exploitation may be represented as a function of the changing abundance, and changing age, sex, and size structure of the population. The response by the ecosystem to this exploitation, and subsequent feedback affecting the exploited population, is assumed to be represented within the functional form used to describe the biological processes for the fished stock; in age structured models, for instance, this may be assumed to occur within the stock-recruitment relationship. Alternatively, it may be assumed that environmental factors remain constant; for example, parameters such as those for mortality and growth are often assumed to be constant and independent of the density of predators or competitors for available food resources.

As Walters (1986, p.94) notes, "parameters measured as averages across the overall stock are likely to change over time". Recognising that the simplification of the constant parameter assumption may be inadequate, and acknowledging that the exploited population exists within the context of a broader ecosystem, the assumptions of the single species models may be relaxed by assuming that the processes of mortality, growth, maturation, and reproduction remain constant within each of a number of subsets of the period covered by the time series of data, but vary between these subsets. This relaxation requires that, at intervals, data are collected to allow the calculation of a time series of parameter estimates; these parameters may then be incorporated in a piecewise manner within the single species models.

Introduction of Environmental Variables

While the spawning potential of the exploited fish stock remains relatively large, abiotic environmental factors are often found to be closely correlated with observed levels of recruitment. In order to improve the predictive ability of the single species models, an appropriate extension is to represent recruitment as a function of both the spawning potential of the fished stock and selected environmental variables (Caputi 1993); this presupposes sufficient knowledge of the stock-recruitment process to permit establishment of feasible hypotheses and selection of appropriate environmental variables. For example, Penn and Caputi (1986) have had success in incorporating information relating to rainfall (associated with cyclone activity which appears to affect survival of recruits) in modelling the stock-recruitment relationship of prawns in Exmouth Gulf.

Spatial Models

Where the exploited stock covers a wide latitudinal range, it is also likely that density, recruitment, and the rates of biological processes will also vary over that range (Beverton *et al.*, 1984). For such fisheries, it may be essential to consider a spatial representation of the system. Similarly, where different sectors of a fishery fall under the regulation of different management authorities, where area closures are included within the management regime, or where the exploited population exhibits a spatial resolution that varies with age or time, spatial models may be required.

These models may be of either the box type, where the area covered by the exploited stock is divided into a number of possibly irregular regions, or of the grid type, where the area is divided by a regular geometrical grid. Such models require, for each region or grid cell, data similar to those required for the single species model; that is, catch, effort, and abundance data must now be spatially disaggregated. Also, parameters of mortality, growth, maturation, and reproduction must be provided for each region (e.g. Walters *et al.* in press).

Further to this, and peculiar to spatial models, is the need for data on the (possibly age or size specific) flow between adjacent regions, and on the regional distribution of recruits to the exploited stock (arising from the spawning stock within each region). Tagging data become important in estimating rates of migration.

Fishing Effort Dynamics

Traditional single species models treat fishing effort as an exogenous variable; that is, effort is assumed not to respond to changes in the abundance of the exploited stock, but is a variable determined outside the boundary and within the surrounding environment of the model. Recently, there has been greater recognition of the predator-prey status of the fishing fleet and the targeted stock (e.g. Walters *et al.* in press).

In order to broaden the scope of the models, by including effort as a variable predicted within the modelled system, time series data are required on tactics used by the fishing fleet and on the economics of fishing, for example the value of the fish landed, the cost of additional vessels, gear, or technology, and the cost of fishing operations (Table 2).

Multispecies Models

The simplest approach used for multispecies fisheries is to treat the combined catch of all exploited species as a single unit. The species composition that results as the fishery is exploited is not modelled.

Another simplistic approach is to model the dynamics of each species using a "single species" model. Then interaction between the various stocks is usually modelled as technological (operational) interaction (Table 3), where effort expended results in catches of each species, and where the tactical response of the fleet varies with species abundance and market demand (Beverton *et al.* 1984); biological interaction between the species is ignored.

Targeting of effort towards each species becomes important, and the historical time series is usually separated into the effort targeted towards each individual species; data required to determine this targeted effort might include the characteristics of fishing tactics that determine the species mix within the catch at varying levels of abundance of the fish stocks, and detailed records of the tactics and gear used while fishing. If targeted effort can not be determined, it may be possible to identify a subset of vessels targeting each stock allowing abundance indices to be determined for the various fish populations. Alternatively, survey data on stock abundance may be necessary.

A more complex approach is to assume that in addition to technological interaction, biological interaction will occur (Table 4). The latter may take the form of competition for resources (food, space, or shelter), or of predation. Predation is likely to be size and age specific; predation of larvae and juveniles, prior to recruitment to the fishery, becomes important. The abundance of these components of the fish stocks becomes an increasingly important element of the data collection.

In addition to information on each single species, the data set must now include information on (age or size specific) interaction between each stock. Such requirements have seen ICES (the International Council for the Exploration of the Sea) move towards the collection of large amounts of information on gut contents in an attempt to determine the daily ration of each species (Stokes 1992). Switching of food preferences as the relative availability of prey items changes requires continual reassessment of these interaction terms. The spatial distribution of the various species, and the migration patterns of those species, are important factors in determining the level of interaction that may occur between the species.

Ecosystem Models

More demanding still are models of the ecosystem (Table 5). In these models, the physical, chemical, and biological interactions are included in the modelled processes. Information on forcing by temperature, or wind, is combined with information on bathymetry to construct (multilayered) models of water advection and mixing. This information is then combined with data on nutrient levels and inputs, rates of chemical transformation, biological uptake, diffusion, and nutrient release from sediments to estimate concentrations throughout the water mass. Information on the levels of photosynthetically active radiation (PAR) reaching the various depths must be determined, involving knowledge of turbidity, and shading effects of the biota itself.

Information on the rates of primary production is then used, together with estimates of the biomass of phytoplankton, algae, and seagrasses (by species type), to estimate changes in biomass and nutrient uptake that will occur. Loss of biomass through erosion, mortality, or grazing requires information on the rates involved. Subsequently, with interactions through the food web, the biomass of each functional group is determined; as in multispecies models, the data requirements are for detailed information on daily rations and composition of each dietary element, and will involve interaction between size of predator and size of prey.

Here the approach used is often to aggregate the species involved into functional groups or trophic levels. This implies that, although used as an aggregate, information must be available at species level. Commercial groupings and taxonomic groupings are likely to prove inadequate.

Discussion

Data requirements increase exponentially as models become increasingly complex. This imposes a considerable burden on the resources of a research agency, and, with many fisheries, the costs associated with collecting such extensive data bases are likely to become prohibitive. An inevitable consequence is that researchers will have access to data sets that are less than adequate, with the result that stronger assumptions may need to be made in order to use available data, and the resulting models will have considerable uncertainty.

While precision of model predictions is sacrificed as models become overly complex, there are benefits associated with taking a broader view of each system than obtained by relying only on a simple single species model. For example, understanding of the possible interactions is enhanced by the modelling process, and the ability to make subjective judgements regarding the impact of environmental perturbations or changes within the environment is improved.

Often management advice is required on the impacts of environmental disturbance, or the impact on apex predators such as whales or penguins of fishing prey species, such as krill. Here the managers need advice that may require the formulation of multispecies or ecosystem models.

It should be recognised that the consequence of using a model in which the processes are incorrectly described is that the behaviour of the model may differ markedly from the behaviour of the modelled system. Sudden unanticipated collapses have occurred in fisheries around the world (for example, the fishery for the Peruvian anchoveta (Hilborn and Walters 1992)), where the behaviour of the simpler models was simply inadequate because the boundaries of the model had been too narrowly defined.

While simple models are likely to be the first models used to describe a fishery, it is highly probable that as that fishery becomes more heavily exploited, more complex models will be required. Long term time series are essential if such models are to be successfully used. Further, collection of a broader range of data, reflecting the ecosystem of which the fishery is a component, may alert researchers to important interactions between components of the system such that they may be included in the models used. The focus of data collection must be broadened beyond the single species horizon if robust management advice is to be available when it is required at a future date.

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Table 1. Data needs for single species models.

- Stock identification data:
  - Taxonomic data.
  - Electrophoretic data.
  - Morphometric data.
  - Tagging Data.
  - Chemical and biological (parasite) tracers.
- Time series data:
  - Catch data (both discards and landings), disaggregated by gear type, age, sex, size and location.
  - Effort data, disaggregated by gear type and location.
  - Abundance data, disaggregated by age, sex, size, and location.
  - Data on abundance and distribution of parental stock.
  - Recruitment data.
  - Data relating to fishing power.
- Biological data:
  - Weight – length relationship.
  - Growth function.
  - Fecundity.
  - Maturity.
  - Natural mortality.
  - Distribution of age classes and migration processes.
- Technological data:
  - Selectivity of fishing gear.
  - Efficiency.
  - Fishing power.

Table 2. Additional data required to model effort dynamics.

- Economics:
  - Cost of vessels.
  - Cost of fish finding and navigational equipment.
  - Cost of fishing gear and bait.
  - Cost of fishing operations (e.g. fuel used, distance from port, etc.)
- Market:
  - Relationship between supply and demand.
  - Impact of competitive products.
  - Seasonal nature of demand.
  - Dependence of demand on size of fish.
- Tactics:
  - Response by fishing fleet to changing distribution of fish.
  - Response by fishing fleet to historical fishing patterns.

Table 3. Data requirements to model technological interaction.

- Targeting of effort:
  - Catch data disaggregated by target species.
  - Effort data disaggregated by target species.
- How tactics affect catch:
  - Characteristics of fishing tactics determining the species mix.
- Subset of vessels targeting each species.
- Surveys to obtain fishery independent data.

Table 4. Data requirements for modelling biological interaction.

- Competition:
  - food;
  - space;
  - shelter.
- Predation:
  - Gut contents.
  - Daily ration.
  - Prey switching and relationship with availability of prey items.
- Size dependence of competition and predation:
  - Larvae and pre-recruits must be considered.

Table 5. Data requirements for ecosystem models.

- Physical:
  - Bathymetry.
  - Tides.
  - Winds.
  - Temperature (depth).
  - Salinity (depth).
  - Currents, waves.
- Chemical:
  - Nutrient levels, sources, sinks.
  - Rates of uptake, release, diffusion, transformation.
- Primary production:
  - Light, Photosynthetically Active Radiation (PAR).
  - Turbidity.
  - Attenuation.
  - Shading.
  - Photosynthesis – Irradiance (PI) curves.
  - Biomass.
  - Growth, erosion, loss.
- Secondary production:
  - Grazing.
  - Filtering.
  - Processing detritus.
  - Predation.

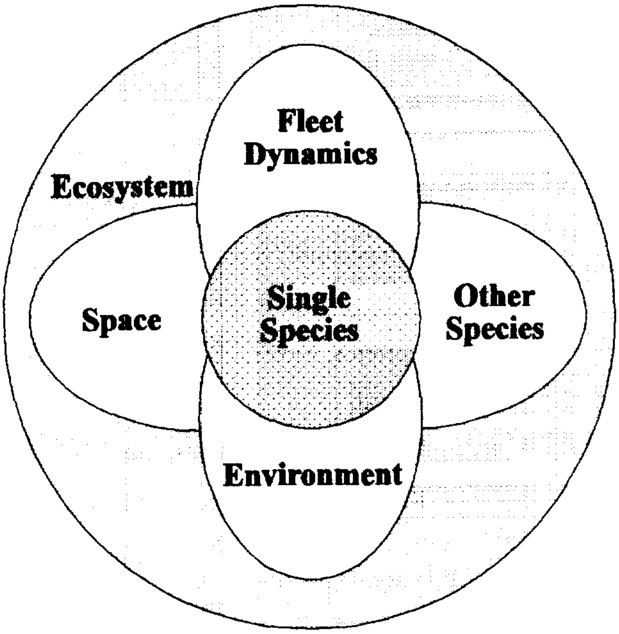

Figure 1. Model boundaries.