Virtual Fish, Virtual Fisheries and Virtual Fishery Management: An Introduction to Fish Heaven

I.R. Ball and A. Constable
Antarctic Marine Living Resources Group, Australian Antarctic Division, Kingston, Tasmania 7050, Australia (ian.ball@antdiv.gov.au, andrew.constable@antdiv.gov.au)

Abstract: Prospective evaluation of fisheries management strategies is becoming a more common way to determine how well fisheries will perform in relation to a number of metrics including the status of a fish population and the economics of a fishery. Plausible models of fish populations and the behaviour of the fishing vessels are used as "laboratories" to test how well decisions can be made to achieve sustainable fisheries given uncertainties in the data being obtained from the natural and fishery systems. This paper presents a new simulation package *Fish Heaven* which is designed for this purpose. It is different to other packages in that it is a spatially structured model while maintaining a great level of user-control in the dynamics of the fish stocks, the configuration of the spatial environment and the operation of the fisheries. Fish Heaven is described along with the issues that it was designed to address. This is followed by early results from a case study using the software to test the efficacy of Catch Per Unit Effort as a measure of relative abundance for a spatially structured population.

Keywords: Catch-per-unit-effort; Monte Carlo Simulation; Management Strategy Evaluation

1. INTRODUCTION

One approach to the evaluation and formulation of fishery management strategies involves the use of simulated populations and simulated fisheries [de la Mare 1986, 1996, 1998; Cooke 1999]. The effectiveness of a management strategy and use of management measures can thus be tested in this virtual world. Important questions can be asked in the controlled and idealised world of the simulation. Can significant decreases in population size of the fishery be recognised in sufficient time for action to be taken to ensure the long-term sustainability of the stock? What measures will be most effective in sustaining the stock as well as the fishery given the uncertainties in knowledge about how the natural system works and uncertainties in the data acquired from the fishery and other monitoring programs? In other words, what management system is going to be most robust against these uncertainties while enabling the development of a fishery.

This paper introduces a fishery simulation model "Fish Heaven" that has been designed for this type of management strategy evaluation. It will be demonstrated in the context of testing the efficacy of a common measure of relative abundance – Catch per unit effort (CPUE).

Catch-per-unit-effort data are widely used in managing fish populations [eg Cooke, 1985; Richards and Schnute, 1986; Pet et al 1997]. The data are common and readily available in many fisheries. CPUE is theoretically a good measure of the relative abundance of a population under a few broad assumptions such as an equal catchability of fish and an evenly and well mixed population [Hilborn and Walters, 1992] although its utility as an indicator has long been questioned [e.g. de la Mare 1984; Peterman 1990]. Under a number of spatial situations CPUE is expected to be a poor measure of relative abundance.

When the population is mobile but attempts to distribute itself optimally across a heterogeneous landscape it is no longer evenly distributed in the manner expected under the CPUE measurement. In this case MacCall's 'basin model' is appropriate [MacCall, 1990]. In this case the density of individuals in a location is a function of the relative quality of the habitat at the location for that fish, in the absence of fishing. The density at the richest locations will change only slowly as the population size changes, instead it is the range of the fish that will expand and contract as the population size changes.

This paper has two parts. First, Fish Heaven is described. Second, the model is demonstrated using early results of an evaluation of CPUE as a determinant of relative abundance. This application has provided the early impetus for the development of the software.

2. THE MODEL

Fish Heaven is a fish and fishery model which includes a two dimensional habitat, an age-structure fish population and a fishery. The fishery is modelled either as distributed effort or as a number of boats with different fishing strategies. It was designed to enable the evaluation of and experimentation with a variety of management strategies governing longline fisheries. Key elements of the model include:

- Fish population controlled by standard life history parameters,
- Age structured population (Stage/Size structure also supported),
- Stochastic recruitment, mortality and fish harvest,
- Correlated inter-annual variability in recruitment and mortality possible,
- Catastrophes as occasional or programmed occurrences,
- Two dimensional spatial structure,
- Single variable habitat quality measure,
- Fishery modelled as distributed effort or as agent (boat)-based model.

A number of the elements are designed with rising complexity and alternative constructs. For example recruitment can be flat, or log-normal or follow Beverton-Holt density dependence [Beverton and Holt, 1957]. The stochasticity of events such as mortality and fishing can be included as a fixed proportion or a random number taken from a binomial or normal distribution or even a context-determined random number (binomial for small and normal for large populations). This allows the user to balance and test the trade off between computational efficiency and complexity.

The landscape consists of a grid of hexagons, the number and scale of which are controlled by the user. Thus, the model can be run with no spatial structure (1 hexagon) or considerable structure. The structure of the program is designed so that it will be easy to support maps containing arbitrarily sized and shaped locations as well as grids. Movement of fish between adjacent hexagons can be as many movement periods within a year as the user wishes, although map size and movement frequency are the main factors determining execution time of the program.

Each hexagon has a value called the habitat quality. This value drives the movement of the fish and in the absence of fishing will determine their distribution across the landscape. The fish attempt to distribute themselves so that the ratio of habitat quality to fish population is equal in each hexagon. If the habitat quality represented a food resource this means that, in equilibrium, each fish would get an equal share of the food resource. The habitat quality is an abstract quality that determines how desirable a location is for a given fish. The quality and distribution of the fish have no effect on recruitment or non-fishing mortality. Redistribution of fish occurs through local movement pressures – if an adjacent area has a better ratio of density to habitat quality then fish will move there.

3. TEST CASE

How good is catch-per-unit effort as a measure of the relative abundance of a fish population? If the population is well mixed and there is no selection bias in the fish which are removed then it should be a good measure.

In order for Catch per unit effort to be a good measure of relative abundance of the fish population the catch per unit effort should change as the abundance changes. It should change proportionally so that for a constant effort, if the population were halved the catch would also be halved. The variance of the ratio of catch to effort should also be low so that declines are clearly distinguishable from normal variations.

When the fish do not mix evenly but attempt to distribute themselves according to an ideal distribution then it is expected that CPUE will not be a good measure of relative abundance. As fish redistribute themselves when the population decreases (due to fishing for example) then the density of fish at the richest spots is expected to decrease only slowly as fish move away from marginal habitats toward these spots.

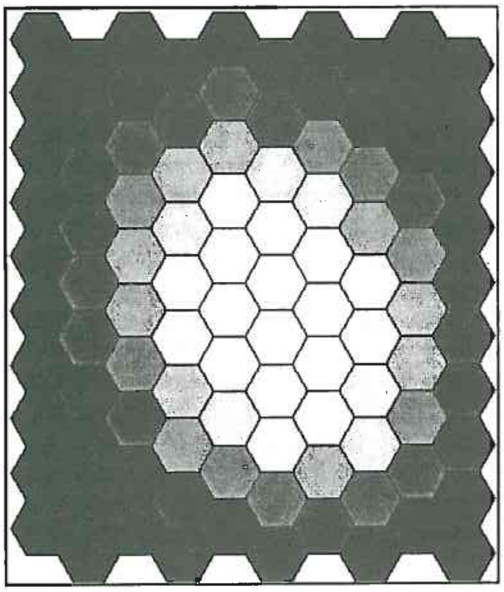

Figure 1. Map showing relative habitat qualities which range between 4.5 (white cells) and 0.25 (black cells) the colour divisions evenly divide the habitat quality range.

This example will examine this effect in a region with one main area of high habitat quality in the centre tapering off to the edge of the terrain. Differences which occur with different sampling strategies will also be examined.

The environment used in this example is a map consisting of a grid of hexagons in ten columns with each column containing ten hexagons (Figure 1). Each hexagon has a different habitat quality that determines the desirability of that hexagon for the fish. The habitat qualities have a peak in the centre of the map and taper off according to a two dimensional Gaussian distribution.

Three types of fish harvesting are examined in this study. These are: Best Density, Best Habitat and Random. In each case ten hexagons are fished at each period within the fishing season which lasts for fifty periods. Thus the effort is constant in each treatment. Best Density fishing should be ideal for the fishery, the hexagons with the ten highest population densities are fished. This gives the instantaneous highest rate of return for the fishery. It assumes that the best densities are known to the fishery. In Best Habitat fishing the ten hexagons with the highest habitat quality are fished in each fishing period. The locations with the highest habitat qualities will be the ones with the largest densities when the fish have distributed them ideally. During a fishing season this distribution will be perturbed by fishing and these locations are not expected to have the highest densities throughout the season. The final method is Random in which the effort is distributed randomly at each fishing period.

It is expected that Best Density fishing will give the highest catch and that the Random fishing will give the lowest catch. From this we will determine whether catch per unit effort a better measure of relative abundance for one or another fishing method?

The life history parameters of the fish are set to be those estimated for the Patagonian Toothfish [SC-CAMLR, 2000]. Notably recruitment occurs outside of the fishing season and the new fish are distributed randomly across the terrain to start with. They enter the stock at the age of four and there is no selectivity with the stock biasing the catch toward fish of a given size or age.

In order to control the size of the population the average recruitment is varied. In the first of the two experiments the recruitment has been set so that the fish population will decline rapidly to a small fraction of its pre-fishing equilibrium. There are one hundred separate simulations with identical starting conditions in this experiment.

In the second experiment the recruitment is varied between treatments to give different population equilibria for each treatment. Each treatment contains one hundred trials to allow the variance of the results to be examined.

For CPUE to be a useful estimator of relative abundance, the ratio of CPUE to stock biomass should remain largely unaltered with respect to the status of the stock. Given that fishing effort is constant across all trials in each experiment the output is given in terms of the catch biomass divided by the stock biomass.

4. RESULTS

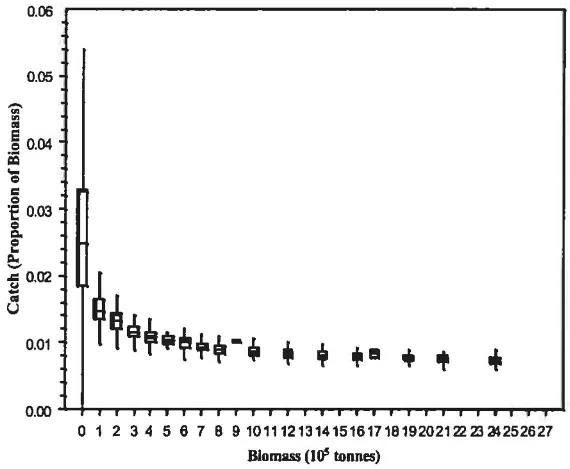

Figure 2. Level of fishing success in terms of the fish biomass. The y-axis is the catch as a proportion of the fish biomass. The x axis is the biomass.

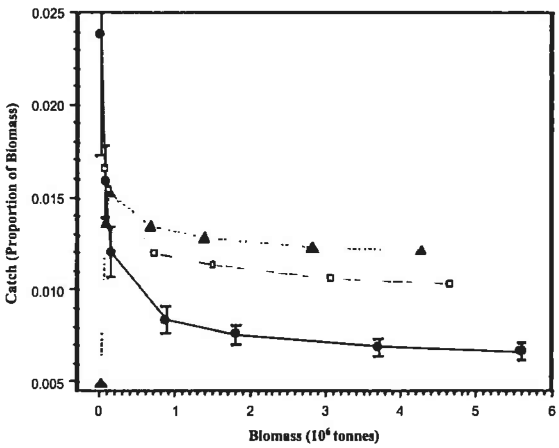

Figure 3. The three lines represent three fishing strategies: Random fishing (circles), Best Habitat (triangles) and Best Density (squares). Each point represents a summary of one hundred runs at a different biomass. The variance bars displayed on the Random fishing strategy are indicative of the variance of all three strategies.

In the first experiment the population decreases as fishing continues and the relationship between the catch and the biomass is displayed in Figure 2. The effort is the same in each year in the experiment. When the biomass is low the ratio between the catch and total biomass is relatively high. It is lower and more even when the biomass is higher. The variance in this ratio is displayed as box plots in the figure.

The results from the second experiment are displayed in Figure 3. In this experiment as the biomass decreases the ratio between catch and biomass increases. This is generally the case with the exception of the Best Quality fishing treatment which shows a sharp decrease at very low biomass levels. The Random fishing method produces the worst catch at high levels of biomass but these become closer to the Best Density method at low biomass. At higher biomass the Best Quality method does better than the Best Density method. The variance in the catch proportion increases as the biomass decreases, at low levels the variance is very high.

5. DISCUSSION

The proportion of fish biomass caught in both experiments exhibits an increase as the biomass decreases under constant fishing pressure. At high biomass the proportion is relatively stable but it increases rapidly at lower biomass in most cases. If we were to assume that CPUE was a good measure of relative abundance in these experiments then we would tend to over-estimate abundance in cases when the biomass had been reduced to below 20% of pre-exploitation abundance and in most cases this could be as much as by 2-3 times. Figure 2 also demonstrates that the variance at the lower biomass is much greater which will also lead to significantly inaccurate estimations of abundance at low levels. Because increased care in the management of the fishery is required at low levels these results are important.

Figure 3 demonstrates the differences between the three fishing strategies. In each case the proportion at lower biomass is very different than at high biomass. The Random strategy has the lowest catch proportion at high biomass but increases to a level similar with the Best Density strategy at lower levels. The explanation for this is probably that at lower biomass levels the fish are distributed more evenly across the landscape.

The movement pressures are lower at low biomass and the localised effect of fishing can be significant.

Interestingly, the Best Quality strategy outperforms the Best Density strategy at high biomass but does very poorly at low biomass. This invites further experimentation. Probably the reason is that at high biomass the Best Quality locations maintain a high density with constant movement pressure pushing fish toward them. At lower biomass the movement pressure is lower and these High Quality environments are fished out early and are not replenished within the season. The Best Density strategy will start fishing in the same locations within a season but will then fish across the landscape so that the movement pressure will tend not to be localised to the centre of the map but more evenly spread. The Best Density strategy will tend to push the fish toward a more even distribution.

6. CONCLUSIONS

The experiments on CPUE indicate some weaknesses on their use as a measure of the relative abundance of a fish population with the spatially heterogeneous landscape that was modelled, consistent with findings elsewhere [de la Mare 1984]. CPUE was particularly poor as the population grew lower and would lead to inaccurate and overly optimistic prognoses. With a high variance in catch proportions there is an even stronger indication of the caution with which CPUE should be treated.

Even if CPUE is not a good measure of relative abundance it might still signal a large change in relative abundance. The way to test this would be to simulate a number of time series in which the catch data are used to predict the change in the abundance of the population. In some of the treatments the population would be subject to a perturbation and the number of times in which this is detected could be measured against the number of times the perturbation is missed and the number of times a perturbation is falsely identified in the unperturbed treatments.

Other experiments which would complete the examples in this paper include:

- The map was a very simple and well connected map with a high quality location in the middle tapering off to lower qualities. A more heterogeneous map could be created with a few discrete high quality centres. Fishing could also be restricted to just a part of this distribution.
- Can the use of CPUE be improved when there are some research boats pursuing a different strategy than the rest of the fleet, such as randomly fishing or ensuring a wide spatial distribution of efforts.
- To what extent are the above results driven by the movement speed of the fish. To what extent would the results be different if the species was slow moving, very slow moving and nearly immobile?
- How large would a drop in the population have to be in order for it to be detected 50% of the time with a 95% certainty? How long would the population have to decline, or be subject to a changed recruitment regime, before the change was detected using CPUE?

Fish Heaven allows the inclusion of many more features than were used in this trial. More complex life history modelling is available and the fisheries can exhibit more complex and realistic fishing behaviours. The software is designed to be easily used with a fully documented graphical user-interface and controls to allow for detailed sensitivity analyses, mixing ordered with random parameter variation. It was designed to allow extensive research into management strategy evaluation as well as to be an approachable package for demonstrating established principles.

Fish Heaven is a fully documented and tested model but one which is undergoing continuing evolution and extension. Additional planned features include:

- Extension to multi-species systems.
- More complex landscapes. Moving away from hexagonal grids to arbitrarily defined planning units.

The use of modelled fish population and modelled fisheries allows management strategies and management measures to be evaluated in a way that could not be done in the real world. Robust and approachable models such as Fish

Heaven can have a tremendous value in exploring and explaining such new ideas.

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