1 A Bayesian Approach To Coral Reef Fishery Stock Assessment

2 Introduction

The project aimed to develop a method to provide scientific advice appropriate to small scale fisheries. Such fisheries are characterised by dispersed fishing activity, diverse catches and subsistence fishing. These factors make data collection based on normal methods such as log sheets and sampling landings difficult if not impossible. The new method presented here relies on two approaches. For parameters describing the long term dynamic behaviour of the fishery, information is obtained from fishers through interviews. For parameters describing the effect of fishing on the stocks or status of the resource, direct information can be obtained from short term fishing experiments. These sources of information are combined using a Bayesian approach.

The stock assessment model is a species-combined yield approach based on the Schaefer model. Although the model takes little account of ecology, it is relatively robust and should provide guidance on fishing levels in the form of overall quotas and numbers of fishermen.

3 Model

The stock assessment model used was the biomass Schaefer model, based on the logistic equation describing population growth and a linear relationship between CPUE and stock size. The model requires three parameters: r = the rate of population growth, K = unexploited stock size and q = catchability. In the difference equation form, the model is written:

$$B_{t+1} = B_t + rB_t\left(1 + \frac{B_t}{B_\infty}\right) - qf_t B_t$$

The model can be used to define the limit reference points, MSY = $rB_\infty/4$ and Effort at MSY = r/2q. These two quantities are the values of interest and will be used to advise management by suggesting precautionary limits to fishing capacity.

The parameter probabilities are interdependent, so it is necessary to model the prior and posterior as a joint probability distribution. This increases the complexity of the analysis, but does allow correlations between parameters to be correctly taken into account and therefore yield robust estimates of the reference points of interest.

4 Data Sources

4.1 PRIOR KNOWLEDGE: FISHER INTERVIEWS

It is not possible to ask directly what parameter values should be as fishers are unfamiliar with the model. Instead questions were asked of variables for which it was thought fishers would have some knowledge, or at least an opinion. These variables were then interpreted in the context of the Schaefer model to provide parameter values.

Interviews were undertaken with 132 fishers. The following questions were asked:

- *What is your current average catch rate with your gear? (**$q_1=qB_t$**)*
- *What catch rate do you think you would have if the reef was unexploited? (**$q_2=qB_{¥}$**)*
- *How long do you think it would take for the fish stocks to fully recover from their current state back to their unexploited state? (**q_3**)*

- *What is the maximum number of fishers do you think the stock can support before the total catch would decline? (**q_4=r/2q**.)*

Fishermen were asked catch rates for each gear they were familiar with and for the hot and cold seasons.

For each fisher the parameters were calculated as follows.

The current stock size as a proportion of the unexploited stock size (X_0) is given as ***q_1/q_2***. For the difference model an unfished population will grow according to the relation:

$$X_{t+1} = X_t(1 + r + rX_t)$$

We solve this equation for *r* where $X_T=p$, *p* = the target proportion of the stock size which cannot be distinguished from unexploited stock size (which is reached only after an infinite time), and *T* = the recovery time given by the fishers (***q_3***). The results are reasonably sensitive to choice of *p*. The coefficient of variation of the mean monthly catch rates over two years was 23%. This includes other sources of variation besides unexplained errors which would be observed by individual fishers. However, the sample size of individual fishers would also be smaller. On this basis we assessed that fishers probably cannot easily tell the difference between 90% recovery and 100% recovery, and chose 0.9 as the value for *p*. The remaining parameters were then calculated using the following equations.

$$q = r/(2q_4 f) \quad \text{and} \quad B_{¥} = q_2/q$$

where f = average effort for each fisher per year taken from two years observations.

The answers were used to calculate the r, K, q parameters of the Schaefer model and these calculated values were used to generate a joint prior distribution. This is achieved through an empirical probability density function using the kernel method described by Press (1989). In essence, the method is asymptotically unbiased and smoothes a discrete frequency to a continuous function of the parameters.

4.2 OBJECTIVE ASSESSMENT: FISHING EXPERIMENT

A relatively unexploited island in Vanuatu was used to base a depletion experiment. Three 200m transects were laid 200m apart along the southern edge of the island. Visual census counts were conducted over a three week period. Selected species, most of which appear in the catches, were counted within a ten metre band along the transect. Of these, those species which appeared more than twice in the catches were summed to create an index of biomass. After one week, spear-fishers were invited in to deplete the resource, first on the middle transect for four days, then on the western transect for a further four days after they had complained about the low catch rates on the first transect. All fish caught had their lengths recorded. These were converted to weight using length-weight relationships. Average weights were used to convert catches and counts to biomass.

The counts indicated a significant difference in abundance among the different transects. Neither transect registered a significant decline through fishing on the other transect, suggesting transects can be treated as separate populations for the purposes of the current analyses. The model required three parameters. As the island was relatively unexploited, initial population size for each transect was assumed to be drawn from a mean density which was proportional to the biomass for the entire fishery, calculated based on the total area as 5.7km^2. A second parameter was the catchability for spear-gun, which is the mean proportion of the stock removed per man-hour in each days fishing. A third parameter, the mean proportion of the stock seen in each visual census count was a nuisance parameter, and was removed by numerical integration, assuming a uniform prior 0-1. The likelihood for all parameters was based on Student's t distribution for the square root of the observed biomass (catch or count) and expected biomass estimated by the model. The scaling statistic was calculated as the sum-of-squares difference between observed and expected catch estimated from the overall mean CPUE.

4.3 UTILITY

As well as obtaining joint probability distributions for parameters, which can be used to generate probability distributions for relevant management controls, what is also important is some quantitative measure of what the fishing community wants from its fishery. By converting differing levels of catch and employment to a single variable gives an automatic weighting towards the community priorities. This was addressed in two ways:

- The classic approach, to directly assess utility in the form of risk games, was tested. By asking members of the fishing community preferences between different 'games', each with different pay-offs and probabilities of outcomes, generates utility curves. Unfortunately the method is complex for the interviewee and very long. In particular, it was difficult for interviewees to appreciate the 'what-if' nature of the game, bringing answers very much into doubt. It was found to be an inappropriate method.
- A second method was to look at current household budgets, and prospective budgets should households have more or less money. These data could be used as a basis for developing utility curves. This method suffered a similar problem to the risk games method above. Although reasonable data on current budgets can be obtained, 'what-if' questions met with little response from interviewees. Again these contingent questions are complicated, and there is no guarantee that the answers correspond to how households would really react to changes.

Unfortunately neither method succeeded. Given the failure of the two methods, two *ad hoc* utility curves were used. A risk indifferent curve was used which has a linear relationship with observed variables: catch, profit, employment etc. A risk averse curve was used which favoured subsistence catch and the current employment (effort) over increases in either.

Measuring how the community might value different changes in the fishery should be assessed. Contingent valuation is receiving increasing attention in environmental economics and methods look promising. These methods should provide a basis for ensuring community wishes are taken into account in setting fishing controls, which should obtain greater community support necessary for co-management.

5 Method

The posterior was generated as an unnormalised function of the parameters:

$$h(r, B_\infty, q) = p(r, B_\infty, q)\, L(B_\infty, q)$$

While the function can be calculated at individual points, it is not practical to integrate it using standard numerical techniques. Instead two Monte Carlo methods were used. Rejection sampling was to draw random parameter sets from the posterior, and importance resampling was used to provide estimates of expected values (Gelman *et al.* 1995). Both methods work well with a good approximation to the underlying function. A trapezoidal approximation was calculated over a grid of points. The grid was adjusted as much as possible so that vertices lie on modes. Even so, it was difficult to obtain a good approximation and the grid therefore consisted of a large number of points, which slowed the analysis.

In all cases, parameters were constrained to be positive. In addition, the parameter r was limited to a maximum value of 2. Values greater than 2 begin to produce specific deterministic behaviour, which is an artefact of the model rather than a possible population behaviour. Otherwise, for practical purposes, limits on parameters were chosen which covered all but an insignificant proportion of the posterior probability. This should be noted particularly for analyses involving the prior below, for which a significant probability mass lies outside the constrained area (see Figure 1).

6 Results

6.1 PRIOR AND POSTERIOR PDF

The posterior PDF indicates two hypotheses with respect to parameter values, represented by two modes. One favours higher r and q, but lower B_∞, the other higher B_∞, but lower r and q. The former hypothesis was mostly supported by the majority view of fishers. The experiment provides greater support for the higher B_∞, although clearly, based on the current information, either could turn out to be correct.

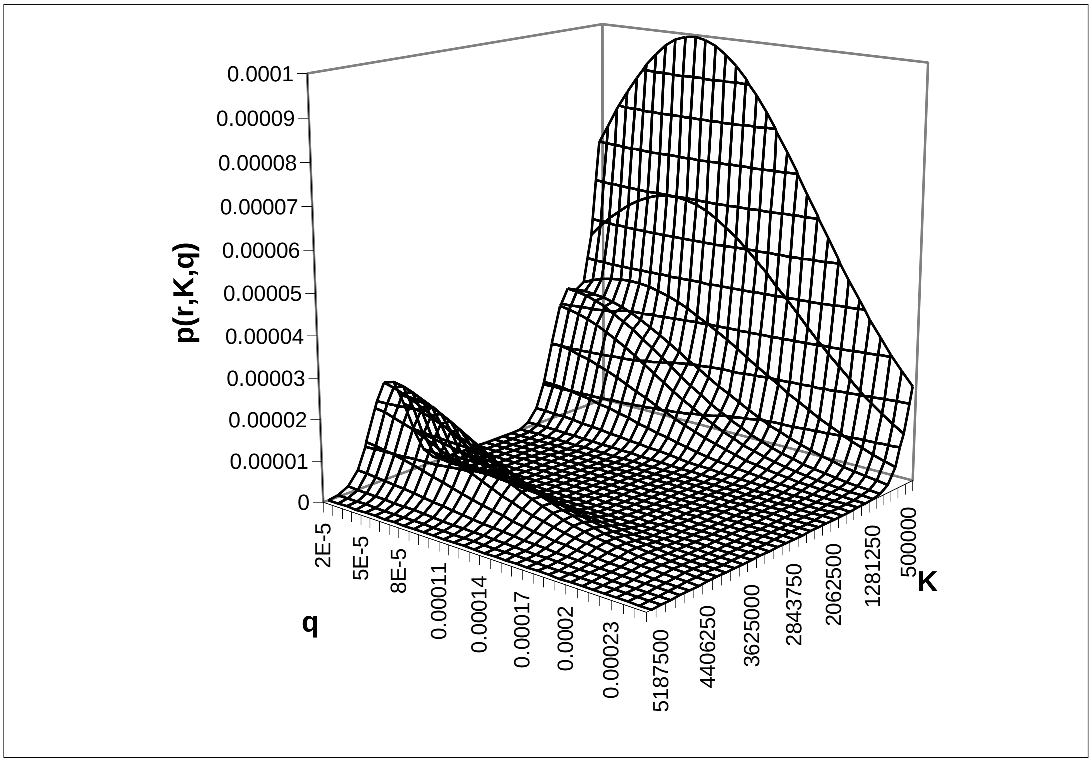


Figure 1 The prior probability distribution for B_∞ (K) and q, and fixed r (0.3125) generated from the interview data. A significant proportion of the probability mass lies outside the parameter constraints, which were chosen on the basis of the posterior for construction of the trapezium. However, the two hypotheses, represented by the separate modes, between low and high K are evident, as is the fact that the majority of fishers support the idea that the population is small.

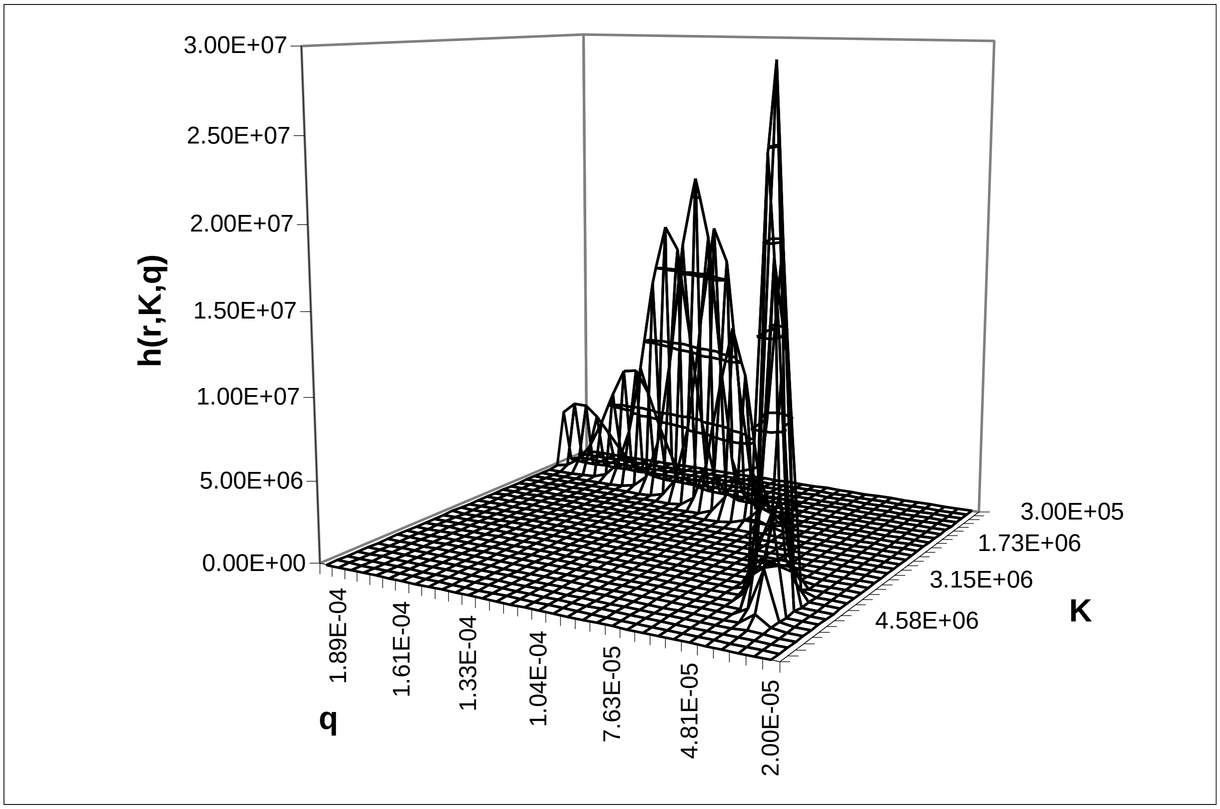


Figure 2 Posterior probability for fixed r (0.625) illustrating two modes for high and low B_∞ (K). The likelihood supports the higher B_∞, and has a significant effect on the prior, which nevertheless remains very influential.

6.2 MSY AND EFFORT AT MSY PDF

Frequency distributions are unavailable for the posterior due to problems with the rejection sampling technique and the approximate function. These can be obtained with a little more work. For the prior, the cumulative frequency of MSY (Fig. 3) and fishers at MSY (Fig. 4) give contrasting results. In all but extremely unlikely cases, the MSY is much higher than the catch obtained. In contrast, numbers of fishers are at the 50 percentile. This would suggest a precautionary approach would be to reduce numbers of fishers to, say, 25 percentile (30) while exploring ways to increase yield.

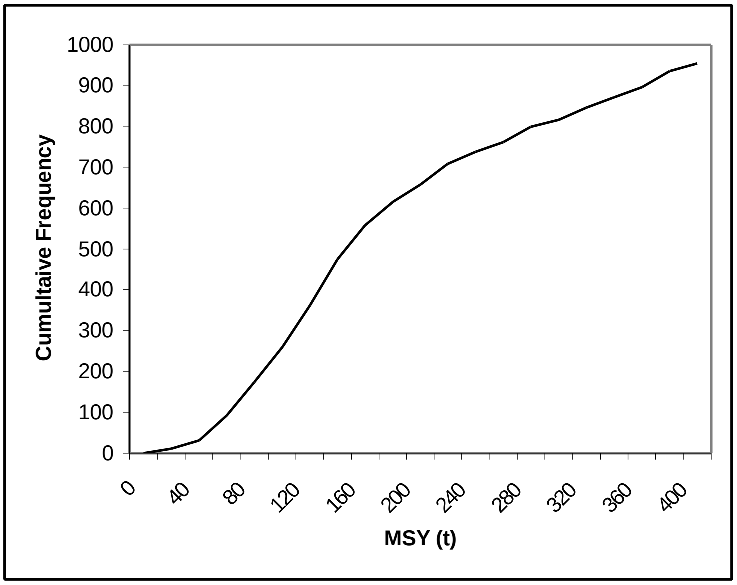


Figure 3 Cumulative frequency distribution for MSY based on random parameters drawn from the prior pdf.

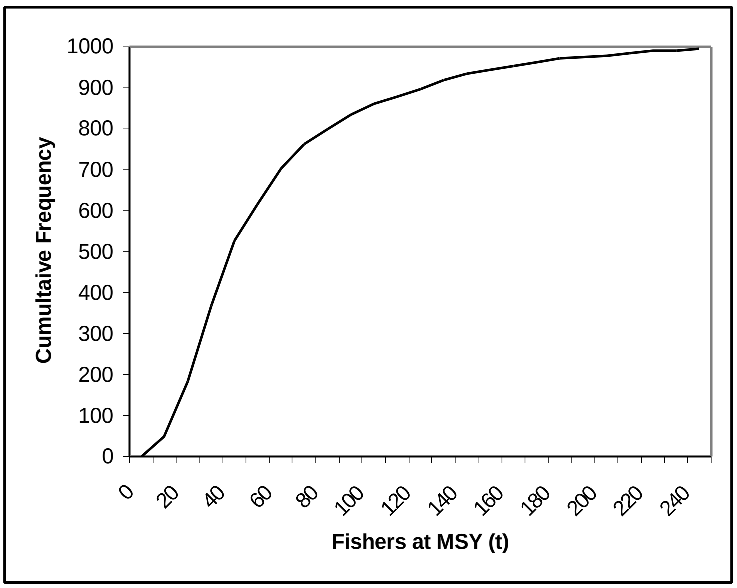
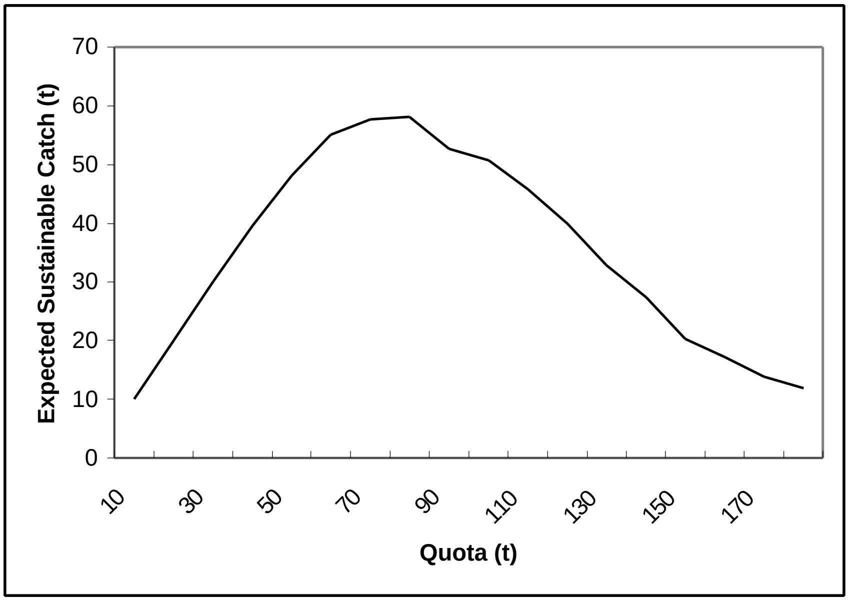


Figure 4 Cumulative frequency distribution for numbers of fishers to reach MSY based on random parameters drawn from the prior pdf.

6.3 DECISION THEORY

Utility was defined as the long term sustainable catch for fixed quotas of catch and fishers. Where overfishing would occur (quota exceeds MSY or fishers exceed those required to reach MSY), the utility is set to zero. In practice, subsistence needs are easily covered by available catches, so more heavily weighting subsistence catch value this has little bearing on the results.

In general, the results suggest that the potential yield from the whole reef is much higher than that currently attained (Fig. 5), and therefore that a high quota could be set which under current circumstances would be superfluous. This is very dependent on exploiting the entire reef area, and on the relatively high estimates of r given. If population growth depends on immigration, the high r estimate depends on the large unexploited area, so any potential yield may be overestimated. In contrast, there is strong agreement between the prior (fishers opinions) and posterior in setting limits on numbers of fishers (Fig. 6). This calculation does not include B_∞, and therefore does not directly depend on the effective fished area. These results suggest that reducing the numbers of fishers could increase yield, if otherwise current fishing practices were maintained.



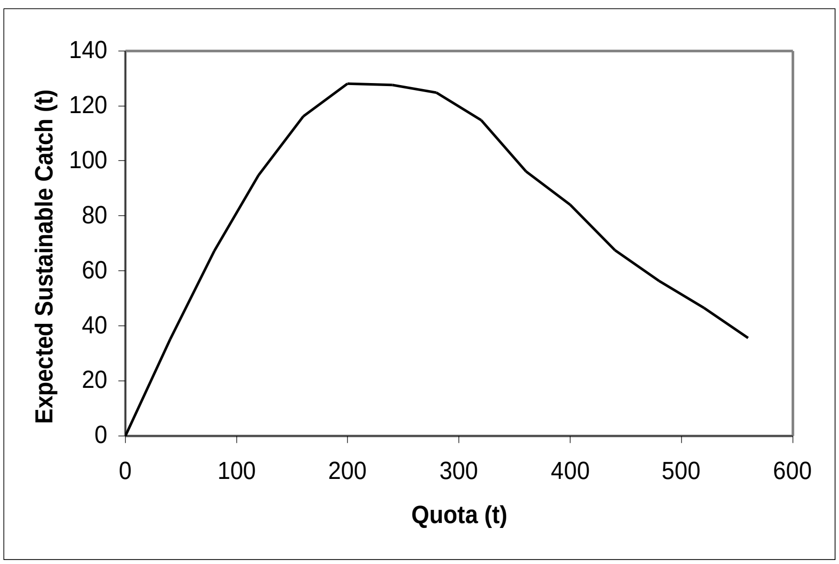
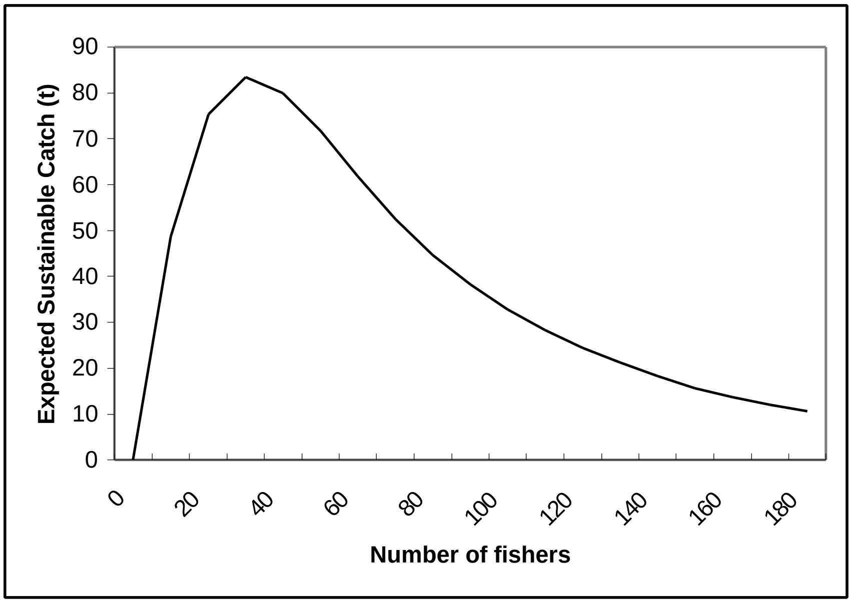


Figure 5 Expected long term catch from different quotas based on the prior (top) and posterior (bottom) distribution. Quotas exceeding MSY gave a zero long term catch. The quota considerably exceeds the annual average catch from the two years observation which was around 13t in both cases. The posterior indicates a much higher potential yield, but this depends on a common interpretion of the model, and that reference is being made to the same area.



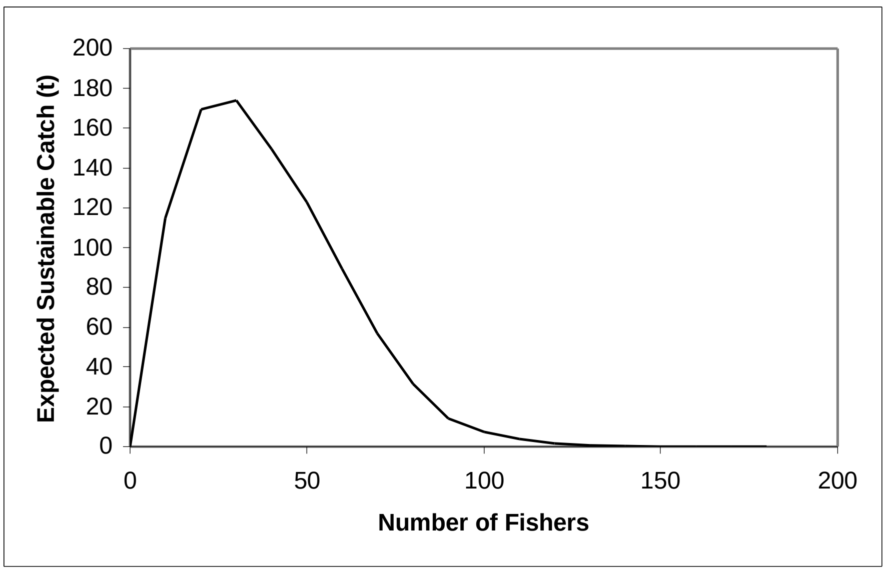


Figure 6 The expected long term sustainable catch obtained from different numbers of fishers for the prior (top) and posterior (bottom) pdf. The current numbers of fishers, 50, just exceeds the optimum sugested by both prior and posterior to be 30. However the expected catch is well above that which is actually attained in both cases. From the interviews fishers felt the current stock size was only 30% of the unexploited stock size, suggesting overfishing at least locally. This may in part be a cause of the lower catches. However, the agreement between posterior and prior in setting numbers of fishers compared to those estimating catch strongly suggest the effective fished area, which is unknown, is heavily affecting the estimated scale of catch, and may be much lower than that found in this analysis.

7 Conclusion

The method provides a general framework for carrying out rapid stock assessment to provide management advice to small scale fisheries. It requires both fisher interviews and short term experimental data, and obtains estimates of important reference points for guiding management. However, the analysis raises a number of issues, in particular the affect of the model assumptions, which are potentially large.

The majority fisher view, that recovery times would be rapid, is represented in the posterior PDF as the mode for high r and q, and low B_∞. This experiment data contradicts this view, with strong indications that the unexploited biomass is greater than that suggested by the fisher interviews. Are the fishers simply wrong, or is this difference due to incorrect interpretation of the interview data?

Answers to interview questions were not used directly, but manipulated to provide fisher beliefs of parameter values in the context of the adopted model. This interpretation is not necessarily correct. For instance, in estimating the recovery times, it was not clear whether fishers drew a distinction between recovery of population size and recovery of catchability as fish became less wary of spear fishers. This would tend to introduce a bias in higher r values than truly exist. However, these values also correlate with B_∞, so the joint pdf favours lower values with high r. Hence the final management controls are robust to these errors where the prior is used alone. The interaction between the prior and experiment likelihood is less clear, as there is little room for interpretation of the experiment model, which produces good estimates of density and q. However, estimates of r rely purely on the prior, and past experience of fishers. Fortunately, the prior reflects no strong belief in recovery time amongst the community, and therefore uncertainty in the r value are probably well represented. Data pertinent to resolving this issue could be obtained from monitoring recovery times of closed areas, the probable source of fisher beliefs on this issue.

A second interpretation problem is biomass. Catch composition is important to fishers, but no weighting for the value of different species in the analysis. This was particularly apparent from the experiment, where although the main target group, scarids, show a clear decline in abundance in the counts, other species do not to the extent that overall, including non-fished species, the visual census shows a slightly increasing trend in biomass on the reef. Again the analysis indicates greater potential yield than fishers achieve because of this selectivity in terms of value and changing catchability of the catch composition. This could only be address through analyses including species composition.

Another important assumption is the fishing area. The calculations assume reference is being made to the full reef area available to the fishers rather than the area they use. The fishers may implicitly apply a weighting to areas based on visit costs (e.g. distance to site), which will effectively limit the stock size to those areas accessible to them. This means the experiment model and prior are referencing different parameters, and that the B_∞ parameter should be scaled downwards accordingly. Without this information, the results must be used carefully. In general, they suggest overfishing is unlikely to occur for the whole area with current number of fishers available and current catches. However, this does not guard against overfishing reefs closer to the village or particular species. Because the biomass yield is related directly to area, it would be possible to adapt the results to account for fishing areas and optimise fishing distribution. However, it might be noted that the high r value suggested by fishers might be related to immigration and therefore the relative unexploited nature of the stock outside the fished area. In this sense the quotas suggested may be optimistic and even if the fishing area was expanded, precautionary controls would be necessary on fishing activity.

If the area being accessed by fishers is small, the results from the prior suggest there are too many fishers and current catches may increase with reduced activity. An alternative option would be to limit the numbers of fishers to the current levels but expand the area of their activity. However, current advice should be to reduce fishing while monitoring catches. If the reefs are overfished, catches should increase.

8 References

Gelman A., Carlin J.B. Stern, H.S. and Rubin D.B. 1995. Bayesian Data Analysis. Texts in Statistical Science. Chapman and Hall, London.

Press, S.J., 1989. Bayesian Statistics: Principles, Models, and Applications. John Wiley and Sons, New York, pp. 237.