DISCUSSION

Comment and reanalysis: paradigms for recruitment studies

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Introduction

"Is recruitment related to spawner abundance?" was addressed by Myers and Barrowman (1996) using the largest data set ever compiled in fisheries (364 time-series). We posed three questions: (*i*) does the highest recruitment occur when spawner abundance is high? (*ii*) does the lowest recruitment occur when spawner abundance is low? and (*iii*) is the mean recruitment higher if spawner abundance is above the median rather than below? We found that when there is a sufficient range in spawner abundance the answer to all three questions is almost always yes. An important aspect of the analysis, and a point completely ignored by Gilbert (1997), is that not all spawner recruit time-series have the same information content. This point is essential in any meta-analysis and is one of several reasons why I cannot accept Gilbert's analysis.

Gilbert (1997) claims, using an earlier version of my data compilation and a method that is totally untested, that the conclusions of Myers and Barrowman (1996) are wrong. He implies that eggs are not in fact required to produce baby fish, and that there is absolutely no need to conserve spawners to ensure future recruits. This is Gilbert's "new paradigm"; however, it is the most commonly used paradigm in what sometimes passes for fisheries management.

The failure to recognize the need to conserve spawning biomass is a principal reason for the disasterous collapse of the formerly great cod fisheries in Eastern Canada (Hutchings and Myers 1994; Myers et al. 1996, 1997). These fisheries were managed using Gilbert's so-called new paradigm, i.e., the assumption that recruitment was independent of spawner abundance. Those wishing to follow Gilbert's advice have many precedents of failure to warn them of their folly. However, I believe that his advice is very popular because it gives an excuse to overexploit now with no concern for future recruitment (again there is hardly anything new about this idea; Huxley 1884). If Gilbert is correct, there should be lots of new recruits in these six cod populations that collapsed in Eastern Canada in spite of the fact of very low spawner abundance. Unfortunately, this is not the case.

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Data

I provided Gilbert with an early compilation of my database used for an early version of Myers and Barrowman (1996) distributed as an International Council for the Exploration of the Sea (ICES) document (Myers and Barrowman 1994). These data were provided before I had published my research. Gilbert had access to a database where many errors had been corrected and the database greatly expanded. He did not use the updated database.

I will provide the data that I have complied to any researcher (Myers et al. 1995*b*, and updates). (I would also like to have access to any such data for fish or invertebrates that any researcher is willing to make public.) Presently, there are over 500 time-series in the database.

On autocorrelation in recruitment

If recruitment is unrelated to spawner abundance then Gilbert had to explain the relationship between spawner abundance and recruitment that was observed by Myers and Barrowman (1996) and others. His suggestion is that it is caused by autocorrelation in recruitment. That is, recruitment may be low for a number of years, which results in low spawner abundance, and then recruitment may increase, for unknown reasons, which will result in a higher spawner abundance. Gilbert's notion is that this may result in an apparent spawner recruitment relationship.

This hypothesis is only reasonable if there are significant amounts of autocorrelation in recruitment. Unfortunately, it is difficult to assess the true autocorrelation in recruitment because of well-known biases and trends in estimation methods. The only study to use multiple research surveys to estimate the true autocorrelation in recruitment was carried out by Myers and Cadigan (1993). They found that many populations had very low, or negative first order, autocorrelation. Gilbert's explanation is unlikely to be a general explanation.

Gilbert explicitly states that Myers and Barrowman (1996) did not address this question. This is simply not true. Although it may be possible to argue that our analysis was not sufficient to deal with the potential problem, we explicitly addressed this issue quantitatively (see Myers and Barrowman 1996, p. 722). I will not repeat the details of analysis here. Also note that Nick Barrowman and I wrote an entire article on estimation biases caused by the presence of autocorrelated errors (Myers and Barrowman 1995).

On untested statistical methods

Gilbert introduces a "method" for testing a regression with autocorrelated data, although there are many well-studied statistical methods for this problem. (A sceptical reader may very well wonder why statisticians do not commonly, or perhaps ever, use Gilbert's methods.) He uses the median of the ratio of the difference in recruitment between adjacent years, ΔR, to the difference in spawner abundance between adjacent years, ΔS, that produced those recruits, as his "regression" estimate.

Gilbert used the median of the $\Delta R/\Delta S$ calculated over years for a stock to argue that there was a stock-recruitment relationship for salmonids but not for marine fish. I will examine this assertion and argue that the method is fundamentally flawed.

What is the median of an apple, a pear, and an orange?

Before examining Gilbert's method we must make a modification so that the results are potentially meaningful when compared among populations. I first ask the following question: Can the median of $\Delta R/\Delta S$, estimated over years for a single stock, be compared across stocks? The median clearly cannot be compared across stocks unless the units in all of the stocks are the same.

Gilbert used the data that I compiled on recruitment and spawner abundance, but no attempt was made to standarize the units in any way (the data necessary to make such standarizations were provided to Gilbert; see Myers et al. (1995*b*), Myers and Barrowman (1996), and Myers et al. (1996) for three methods to standarize the data). The ratio $\Delta R/\Delta S$ will vary by orders of magnitude depending on the units that the data were entered. For example, recruitment may be in units of individuals in one stock and millions of individuals in another stock. This is because I entered the data in the same format as the original assessment documents to minimize errors (I use software to convert into comparable units in my analyses). Since Gilbert did not carry out any standardization, his comparisons among stocks have no meaning, except for the sign.

I will use the proportion of the observations of the ratio $\Delta R/\Delta S > 0$ in a stock as my basic unit of analysis. This preserves the only information that is valid for the median of $\Delta R/\Delta S$, the sign, and provides valid information to scale the value for different stocks as well.

Error amplification caused by dividing by small uncertain numbers

For illustrative purposes I consider the Cushing or Power spawner recruitment relationship:

$$R_t = \alpha S_t^{\beta} e^{\varepsilon_t},$$

where year-classes are identified by a subscript t and the stochastic component of recruitment by ε_t. I use the Cushing spawner recruitment relationship because it is perhaps the case where Gilbert's methods should perform best: there is always a positive relationship between stocks and recruitment. The estimation error is not considered for the moment. The ratio of the difference in log recruitment and log spawner abundance is

$$\frac{\Delta \ln R_t}{\Delta \ln S_t} = \beta + \frac{\varepsilon_t - \varepsilon_{t-1}}{\Delta \ln S_t}.$$

To a very good approximation $\Delta \ln S_t = \Delta S_t / S_t$ and similarly for $\Delta \ln R_t$. Using this approximation,

$$\frac{S_t \Delta R_t}{R_t \Delta S_t} = \beta + S_t \frac{\varepsilon_t - \varepsilon_{t-1}}{\Delta S_t},$$

or

$$\frac{\Delta R_t}{\Delta S_t} = \frac{R_t}{S_t}\left(\beta + \frac{\varepsilon_t - \varepsilon_{t-1}}{\dfrac{\Delta S_t}{S_t}}\right).$$

Clearly, the second term in the parentheses in the above equation can be very large and may completely swamp any attempt to make inferences about the first. The variance of $\varepsilon_t - \varepsilon_{t-1}$ will be twice the variance of the residuals from the fit of a spawner recruit function using log-transformed recruitment. This variance typically ranges from 0.4 to 1 (Myers et al. 1995*a*; Mertz and Myers 1996); thus, the variance of $\varepsilon_t - \varepsilon_{t-1}$ will be from 0.8 to 2.

The critical factor is the size of $|\Delta S/S|$. If this quantity is large (i.e., close to 1) then we should expect that the estimation error of spawner abundance will not overwhelm the estimation process. Clearly, if the year to year changes in the size of the spawner biomass are relatively small (i.e., median $|\Delta S/S| < 1$) then the variability in recruitment, whose variance is already doubled if the estimates are independent, will be amplified again.

What is the size of the error?

The important parameter is thus the relative size of ΔS. I will scale ΔS by dividing by S because $|\Delta S/S|$ enters in the above equations. Furthermore, it is commonly observed in fisheries data that the estimation error variance is proportional to the abundance.

I calculated the mean and median of $|\Delta S/S|$ for each of 364 time-series considered by Myers and Barrowman (1996). The mean for the salmonids is over 10, while it is less than 1 for the other families. (The mean for the salmonids is so large because many pink and sockeye salmon populations have extremely strong cycles.) This is the reason that Gilbert's method "works" for salmonids, but does not for other groups (i.e., the mean $|\Delta S/S|$ is an order of magnitude greater for the salmonids than for marine fish). The median of $|\Delta S/S|$ shows a similar pattern among families.

Thus, we should expect Gilbert's "method" to be reasonable if the mean or median of $|\Delta S/S|$ is larger than the CV of the estimation error of ΔS (recall that the estimation error variance will be approximately doubled because of the subtraction of in the calculation of ΔS). For many families, other than Salmonidae, the median of $|\Delta S/S|$ is around 0.2. This implies that Gilbert's method will be adequate only if the estimation error variance is much smaller than can usually be achieved.

Analysis of Gilbert's result

I used three approaches to analyze Gilbert's claim on the utility

Fig. 1. The proportion of the ratio, $\Delta R/\Delta S$, that were greater than zero versus the median interannual change in spawner abundance, median of $|\Delta S/S|$, for each of the 364 time-series considered by Myers and Barrowman (1994). Note that each point represents a time-series for a population, and two points are off the plot (and are denoted by arrows). Data points from series with fewer than 10 pairs of observations are shown as open circles. If spawner abundance and recruitment were independent, the distributions would be expected to have a median of 0.5. To help summarize the data, curves representing cumulative (from the right) weighted means are superimposed on the plots in each figure (see Myers and Barrowman 1996).

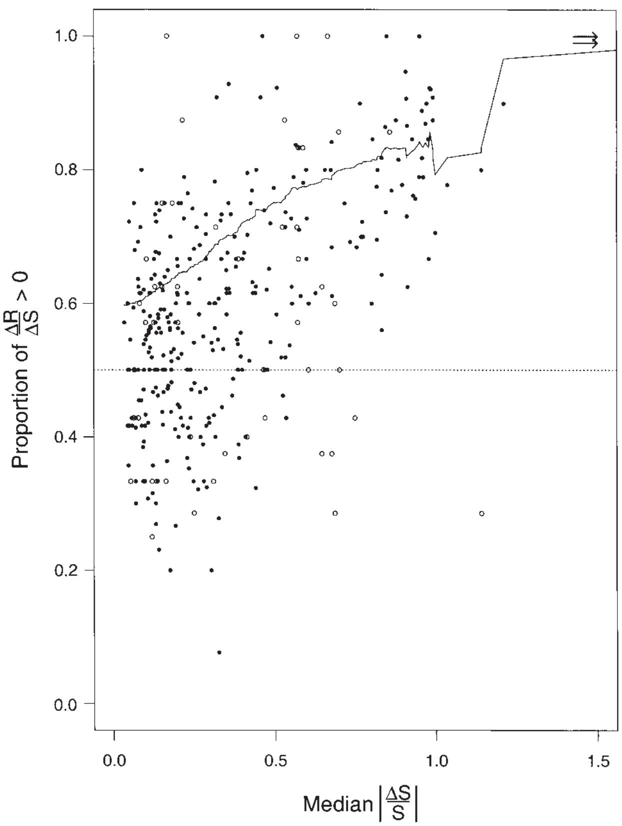
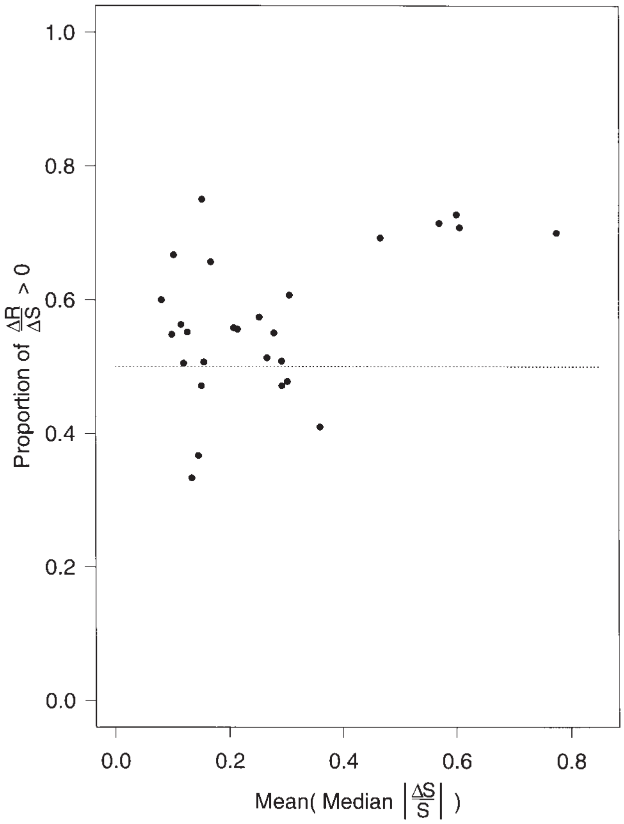


Fig. 2. The analysis carried out in Fig. 1 repeated by family. The y axis is the proportion of stocks in a family for which the ratio $\Delta R/\Delta S > 0$. The x axis is the mean over stocks in a family of the median of $|\Delta S/S|$. Thus, each point represents a family, whereas in Fig. 1 each point represents a stock.



of $\Delta R/\Delta S$: I first examined his claim among stocks, then among families, and lastly among stocks within families.

First, I analyzed if the relationship between the proportion of the observations of the ratio $\Delta R/\Delta S > 0$ in a stock increases with the median of $|\Delta S/S|$. (This is what we should expect if Gilbert's results are an artifact). The results are clear (Fig. 1). If $|\Delta S/S|$ is large, a positive relationship is found. These results are clearly consistent with those of Myers and Barrowman (1996). This suggests that Gilbert's results are a simple artifact.

A remarkable aspect of Fig. 1 is that virtually all stocks with more than 10 data points in which the median $|\Delta S/S| > 0.5$ are not consistent with Gilbert's claim. This result is consistent with the analysis of Myers and Barrowman (1996).

I repeated the above analysis for each family (Fig. 2). The same relationship was found among families: if the interannual change in spawner abundance was relatively high then a positive spawner recruitment relationship was detected. There is one family, Cyprinidae, which consists of relatively unexploited freshwater stocks, with a relatively large median $|\Delta S/S|$ but with a relatively low proportion of the observations of the ratio $\Delta R/\Delta S > 0$.

To repeat the analysis within families, I proceeded by restricting the analysis to stocks in which the median of $|\Delta S/S|$ is relatively large. I first limited my attention to those stocks with the median of $|\Delta S/S|$ greater than 0.5. Nine families had stocks that met this criterion. If we use Gilbert's criterion for a positive spawner recruitment relationship ($\Delta R/\Delta S > 0$ for most stocks), then eight of the nine families show a positive spawner recruitment relationship (the exception is the Clupeidae).

If the criterion for including stocks in this analysis is reduced to the median of $|\Delta S/S| > 0.4$, then the result is similar; the relationship holds for 9 out of the 11 families that have stocks meeting this criterion.

I repeated the above analysis using alternative measures of the extent of error amplification of Gilbert's methods, e.g., the mean of $|\Delta S/S|$. The results were always very similar.

Thus, we can reject Gilbert's hypothesis among stocks, among families, and among stocks within families. The results are completely consistent with Myers and Barrowman (1996).

The notion that eggs are not required to produce baby fish has its basis in the observation that fish are usually highly fecund, which I will call the millions of eggs hypothesis. This was the basis of the old notion that overexploitation of marine fish was impossible (Huxley 1884). However, Gilbert aside, there is now broad acceptance that targets for spawner biomass must be met to ensure stock viability.

Conclusion

I have demonstrated that even though Gilbert's methods are highly inefficient, they can be used to reject his own conclusions, and strongly support the analysis of Myers and Barrowman (1996): recruitment is a function of spawner abundance. The key is to understand that not all time-series are equally reliable. If time-series are separated on the criterion of potential reliability, then we can reject Gilbert's suggestion, among stocks, among families, and among stocks within families.

I believe that great progress can be made in fish population biology by the combined meta-analysis of data from many populations, which are compared with analytical population models and careful experimentation. I cannot accept that Gilbert (1997) provides sufficiently thorough analyses of methods and biases to make important management recommendations, which may have drastic effects on other people's lives.

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References

Gilbert, D.J. 1997. Towards a new recruitment paradigm for fish stocks. Can. J. Fish. Aquat. Sci. **54**: 969–977.

Hutchings, J.A., and Myers, R.A. 1994. What can be learned from the collapse of a renewable resource? Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. Can. J. Fish. Aquat. Sci. **51**: 2126–2146.

Huxley, T.H. 1884. Inaugural address. The Fisheries Exhibition. Literature. IV. **1**: 1–22.

Mertz, G., and Myers, R.A. 1996. Influence of fecundity on recruitment variability of marine fish. Can. J. Fish. Aquat. Sci. **53**: 685–692.

Myers, R.A., and Barrowman, N.J. 1994. Is fish recruitment related to spawner abundance? ICES CM 1994/G:37. International Council for the Exploration of the Sea, Copenhagen, Denmark.

Myers, R.A., and Barrowman, N.J. 1995. Time series bias in the estimation of density-dependent mortality in stock-recruitment models. Can. J. Fish. Aquat. Sci. **52**: 223–232.

Myers, R.A., and Barrowman, N.J. 1996. Is fish recruitment related to spawner abundance? Fish. Bull. **94**: 707–724.

Myers, R.A., and Cadigan, N.G. 1993. Density-dependent juvenile mortality in marine demersal fish. Can. J. Fish. Aquat. Sci. **50**: 1576–1590.

Myers, R.A., Barrowman, N.J., Hutchings, J.A., and Rosenberg, A.A. 1995*a*. Population dynamics of exploited fish stocks at low population levels. Science (Washington, D.C.), **269**: 1106–1108.

Myers, R.A., Bridson, J., and Barrowman, N.J. 1995*b*. Summary of worldwide stock and recruitment data. Can. Tech. Rep. Fish. Aquat. Sci. No. 2024.

Myers, R.A., Hutchings, J.A., and Barrowman, N.J. 1996. The decline of cod in the north Atlantic. Mar. Ecol. Prog. Ser. **138**: 293–308.

Myers, R.A., Hutchings, J.A., and Barrowman, N.J. 1997. Why do fish stocks collapse? The example of cod in eastern Canada. Ecol. Appl. **7**: 91–106.