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Managing fish stocks under climate uncertainty

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The quantitative evaluation of the management of fish stocks under uncertainty requires a formal framework. Decision theory provides that framework. Application of decision theory to fishery management requires information about both the fish stock and the state of the environment. Using Georges Bank haddock as a case study, it is possible to determine the probability of good or poor recruitment using past data and a constant environment. Understanding the state of the environment is more difficult, however, because fixed levels of recruitment, in particular, are associated with different population characteristics, which drastically reduce the sample size for any particular recruitment–environment scenario. Decision theory challenges us to improve our capability of predicting the state of nature, and it appears that this can be accomplished best by reducing the length of the causal chain, a goal now made feasible by the availability of high-resolution, high-frequency ocean models.

Keywords: decision theory, haddock, recruitment.

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Introduction

High-quality management performance is easy to attain in relatively deterministic settings with accurate data and solid decision-making algorithms. However, attaining high-quality performance with limited information in a highly stochastic setting, typical of fisheries management settings, is more difficult. In complex fishery settings, moderate-quality management may be the best that can be achieved.

In order to understand and ameliorate the complexities of fishery management, it is necessary to study the nature of uncertainty associated with the abundance of fish stocks, the effects of fishing, and the influence of the ocean environment. Relating climate uncertainty to fish stocks management is particularly challenging, a challenge that arises when conventional short- and medium-term management issues are placed in a longer-term climate-change context.

For example, interannual variability in recruitment is an important source of uncertainty. It must be ascertained whether recruitment in a subsequent year will be large or small, relative to previous years. Another source of uncertainty is the effect that a single year's recruitment will have on subsequent years (see Rothschild and Heimbuch, 1983, for a discussion of multiple-year adaptive management in a decision-theoretic setting). Further, the dynamic behaviour of fish stocks on climate scales must be determined.

The gadoid outburst in the North Sea is a good example in which multiple-year inference could have been significant. The outburst was a striking phenomenon. Basically, during the gadoid outburst, cod, haddock, and saithe recruitment increased substantially over a period of about 10 years (Cushing, 1984; Rothschild, 1998). This recruitment increased in the presence of increasing fishing mortality, implying increased productivity. At the time, did the observation of the first relatively large year class in the gadoid outburst reflect a single chance event or a major change in productivity? A key question is, could managers have declared an outburst with only one year's information? If so, they could have tuned fishery management decisions to be responsive to a decadal increase in productivity. Could they have declared the existence of an outburst after observing two years' information about large year classes, and so on?

As the focus moves to longer and longer time scales, the nature of information required changes. In the short term, taking account of future recruitment can be relatively simple, since surveys of juvenile fish abundance can be used to estimate future recruitment with relative certainty. In the medium term, average statistics on recruitment can be used to estimate future recruitment. In addition, stock-and-recruitment theory can be used to predict "average" recruitment based on stock size. There are a number of studies that attempt to link stock and recruitment under varying environmental influence, but these generally rely on analyses and synthesis of past data. However, the problem becomes more difficult on climate scales, because the assumptions—that the relation between recruitment and stock is fixed in time and that the ocean environment is constant in time—are not likely to hold. In other words, as interest in longer time scales increases, analysis and forecasts need to shift from a heavy reliance on data to a greater reliance on theory.

In this paper, we attempt to address the problem of making the transition from the shorter time horizons of contemporary management to the longer time horizons of climate-change scale management. To this end, we draw on the concept of decision theory. Decision theory is a well-known set of techniques for analysing performance under uncertainty and levels of risk. In order to implement a decision-theoretical approach, it is necessary to describe the "state of the stock" and the "state of the environment". Describing the state of the stock is relatively easy, since stock and recruitment data are available for many stocks. Describing the state of the environment is more difficult, because the state of the stock and the state of the environment are not easily expressed in probabilistic terms.

In order to analyse this problem, we briefly describe the decision-theoretic framework. Then, we describe a method for evaluating the state of the stock. We focus particularly on the haddock on Georges Bank, because the 2003 year class is the strongest year class ever observed, and therefore seems to represent a very strong environmental signal. Then, we attempt to characterize aspects of the environment related to the strength of the 2003 haddock year class. Interesting hypotheses are generated that contribute to future evaluations of the state of the environment relative to haddock on Georges Bank.

Decision theory

Decision theory is orientated towards quantitative assessment of management decision-making. Decision theory specifies the decisions that might be taken, the risks associated with correctly or incorrectly evaluating environmental variables, and the rewards for any particular management action, taking into account whether the environmental variable is correctly interpreted.

There are three components in a decision-theoretic framework: (i) chance events, (ii) decision makers' strategies, and (iii) consequences or payoffs associated with correct or incorrect interpretation of the chance event (Rothschild and Heimbuch, 1983).

The magnitude of recruitment is an example of a *chance event*. A chance event is defined as an event that has a probability distribution. For this example, the relevant chance event is the state of recruitment or the state of stock-and-recruitment. Recruitment can be considered to be "good" or "poor". The chance event is often called the "state of nature" and is designated by θ. We are interested in the probability of θ, that is, the probability that recruitment will be good or poor. An estimate of θ clearly identifies the level of available information and assumptions. As implied above, we can make various assumptions to estimate θ.

(i) Suppose we have absolutely no information, then we might assign a probability of $p = 0.5$ to a good or poor year class.
(ii) Suppose we have a time-series of recruitment data, and we assume a constant environment, then we might expect the proportion of years having good recruitments to be the same as in the time-series. In other words, using the assumption of constant environment enables us to use the time-series to estimate the probability of good recruitment.
(iii) Suppose we have a time-series of recruitment and stock data, and that we assumed a constant environment, then we might expect the proportion of good recruitment years to be the same as in the time-series conditional on the size of the stock. (Note, this differs from conventional stock-and-recruitment analysis because individual stock and recruitment points are generally considered to be independent; that is, time is not generally taken into account.)

It is clear that this estimate would be improved considerably if information about the state of the environment could be included, particularly in view of the intuitive belief that the environment is changing and affecting the productivity of the fish stock. It is clear that the correct estimation of θ is the crux of management performance. This crucial issue is expressed quantitatively as,

$$P\left[\hat{\theta}=\hat{\theta}_j \middle| \theta=\theta_j\right] \quad (1)$$

In other words, it is desirable that the conditional probability that the "guess" $\left(\hat{\theta}=\hat{\theta}_j\right)$ given the data $(\theta=\theta_j)$ is high.

The *decision-maker's strategies* relate to the decision-maker's guess of the state of nature. If the decision-maker, the manager, thinks that a series of poor recruitment years is likely, then they might want to reduce fishing mortality in the hope of inducing the stock to increase, or *vice versa*. This can be illustrated by an event such as the gadoid outburst, where managers would want to make different decisions based on the level of fishing mortality if stock productivity was low.

The *consequence or payoffs* relate to the utility of the payoff gained or lost by each management action. Here, we can see the implications of uncertainty because, if the manager had perfect information and was therefore omniscient, he or she would always make the right decision, and the utility would be maximum. If information is not perfect, then the manager will not always make the right decision; as a consequence, the utility of management would be less than perfect. From a quantitative point of view, we are interested in the probability of making the right decision given any particular state of nature.

All of these aspects of decision theory can be summarized in a diagram called a decision tree (Figure 1). A sketch of a hypothetical payoff matrix is given in Table 1.

The state of the stock—dynamic setting

This section sets out a procedure based around Markov chain formalism for determining the state of the stock. It is reasonable to think of the state of the stock in any year in terms of its stock *and* recruitment status. The state of the stock in any particular year is given by the stock and recruitment point for that year. We are interested in knowing whether the values of stock and recruitment in any particular year are likely to be different in some significant way in the subsequent year. This implies that stock size and environmental forcing affect recruitment. This is distinct from conventional stock-and-recruitment-based assessments in which the state of the stock in any year is the "mean recruitment" given stock *and* an assumed recruitment-stock relationship (e.g. "Ricker" or "Beverton and Holt"). In other words, in the conventional analysis, each stock-and-recruitment point is considered independently of every other stock-and-recruitment point.

Conventional fishery assessment stock recruitment estimates are not particularly useful when implementing the decision-theoretic method and classifying the state of the

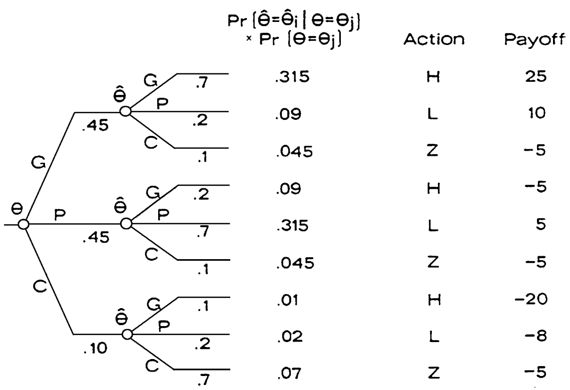

Figure 1. A hypothetical decision tree depicting the effect of sampling and associated decision rules on the probability distribution of payoffs. The decimal number below each branch is the probability of the corresponding chance event. For example, $\Pr(\theta = C) = 0.1$ and $\Pr(\hat{\theta} = P | \theta = C) = 0.2$; therefore, the joint probability for the history, $\theta = C$ and $\hat{\theta} = P$, is 0.02. The decision rules represented are if $\hat{\theta} = G$ then $A = H$, if $\hat{\theta} = P$ then $A = L$, and if $\hat{\theta} = C$ then $A = Z$ (based on Rothschild and Heimbuch, 1983).

Table 1. Hypothetical example of a scenario of costs and benefits of management actions under uncertainty. Note that assumptions need to be made on the relation between fishing mortality and stock productivity.

Management action	State of nature	
	θ = good conditions	θ = bad conditions
A = apply high fishing mortality	High catch, high recruitment, maintain high productivity	High catch, low recruitment, lose high productivity
A = apply low fishing mortality	Low catch, high recruitment, maintain high productivity	Low catch, low recruitment, maintain high productivity

stock. An alternative strategy is to develop an approach that is capable of assessing the probabilistic state of the stock, so that it can be used in the decision-theoretic approach described above. The minimal information probabilistic approach that is both dynamic and non-parametric was developed by Rothschild and Mullen (1985). It involves partitioning the spawning stock into N-tiles and the recruitment into N-tiles. This, in effect, classifies the stock into $N \times N$ states. This classification then makes it possible to study the probability of any state and the transitions among the states (see the example of 2×2 states in Figure 2).

The transition probability matrix provides probabilities that can be used in developing a decision tree. The probabilities are summarized in Table 2. We can see from Table 2, for example, that the highest transition probability is from state 1 to state 2; that the system is in state 2 or 4 most of the time; and that if the system is in state 1, it will take nearly 16 years to pass to state 3, but if it is in state 3, it will take only two years to pass to state 4.

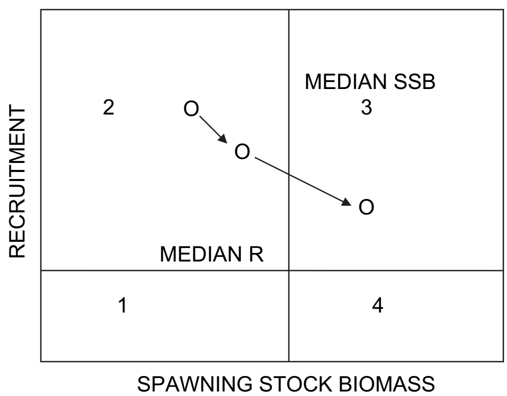

Figure 2. Example of non-parametric representation of the stock and recruitment plane showing $2 \rightarrow 2$ and $2 \rightarrow 3$ transition for three consecutive years (a count of the transitions reflects dynamics).

Table 2. Transition probability matrix, steady state transition probabilities, and expected first-passage time in years for Georges Bank haddock.

Transition probability matrix (p)	To state 1	To state 2	To state 3	To state 4
From state 1	0.38	0.63	0.00	0.00
From state 2	0.45	0.36	0.09	0.09
From state 3	0.00	0.00	0.50	0.50
From state 4	0.00	0.20	0.20	0.60
Steady state transition probability	% of time the system is at state 1	% of time the system is at state 2	% of time the system is at state 3	% of time the system is at state 4
	23	31	17	29
Expected first-passage time (years)	To state 1	To state 2	To state 3	To state 4
From state 1	4.4	1.6	15.9	12.1
From state 2	5.4	3.2	14.3	10.5
From state 3	14.4	9.0	5.8	2.0
From state 4	12.4	7.0	9.7	3.5

The classification of the state of the stock into four states depends only upon stock-and-recruitment information that has been observed. As indicated above, the assumption is that the future relationship between stock and recruitment will behave as it has in the past, and that the past data are drawn from a relatively homogeneous environment. (These assumptions of environmental stationarity are the same as those used in conventional parametric stock and recruitment analysis.)

To ensure at least minimum consideration of the ocean environment in the decision-theoretic analysis, the 2×2 partition can be extended to a $2 \times 2 \times 2$ partition. The 2×2 partition shown in Figures 2 and 3, for example, would be extended to a $2 \times 2 \times 2$ partition, reminiscent of the parametric approach described in detail in Rothschild and Fogarty (1998). The third dimension now represents a "good" environment and a "poor" environment (good might represent high NAO, and poor might represent low NAO, for example). There are now eight possible states. In principle, past data could be used to estimate transition probabilities among eight states, just as it can for four states. But the extension to include environmental information in the simplest way possible becomes immediately complex. The two main problems concerning information involve the choice of a partitioning variable, and the fact that, as we increase the number of states, the number of observed transitions decreases.

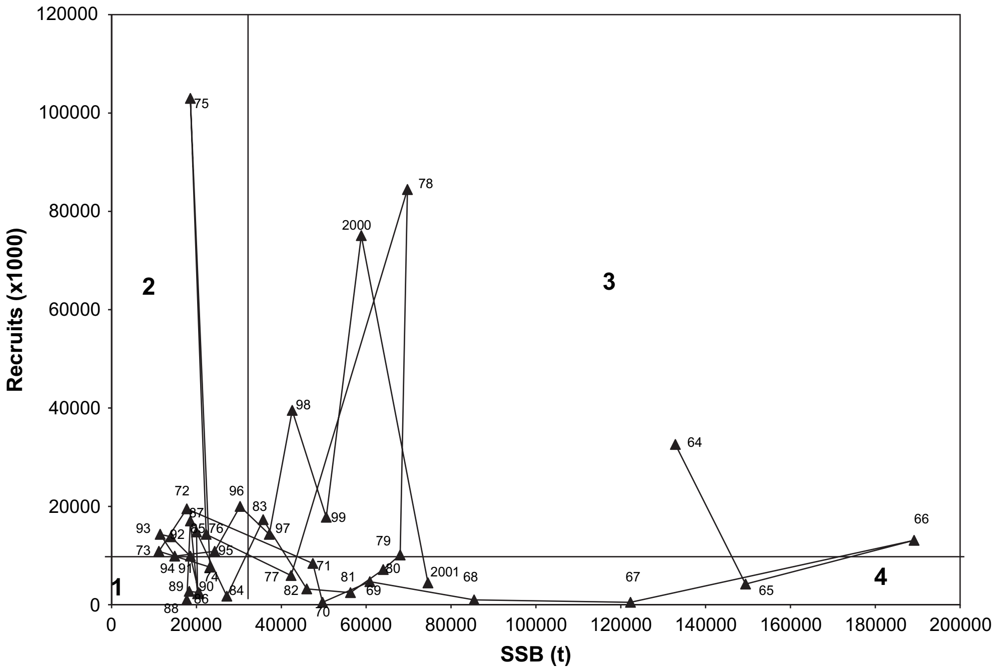

Figure 3. Stock and recruitment states for Georges Bank haddock. The recruitment stock plane is partitioned into $2 \times 2 = 4$ states using the median stock and median recruitment as partitions.

The large year classes of haddock on Georges Bank and the 2003 year class

Hoping to arrive at an eight-state partition, we search for clues by examining the linkage between the 2003 year class and the environment.

The magnitude of the 2003 year class

Figure 4 is a time-series of the relative abundance of age 0 and age 1 haddock on Georges Bank, based on the Northeast Fishery Science Center (NEFSC) bottom-trawl survey. We can see that there are three periods of relatively high haddock reproduction between 1963 and 2004: the 1963 year class, the series of intermediate-size year classes centred on 1980, and the 2003 year class. The 2003 year class is perhaps 40% larger than the 1963 year class; and the 1963 year class is about twice as large as the 1975 and 1978 year classes. We conclude from these observations that years of relatively high haddock recruitment occur sporadically (interestingly, similar to the North Sea—cf. Pope and Macer, 1991).

In the interest of studying common factors that might drive the occurrence of strong year classes of haddock and aspects of the ocean environment, we consider the properties of large year classes of haddock on Georges Bank. These properties include: (i) differing survival rates among years, (ii) egg production, (iii) distribution of young of year, (iv) density dependence, and (v) stock structure.

Differing apparent survival rates

The ratio of the number of recruits to the biomass of spawners (compare Figures 4 and 5) is a rough index of apparent survival. (Note, these data were derived from VPA analysis and are, therefore, somewhat different from the trawl survey data that focus on zero-age fish in this paper.) The ratio of recruitment (individuals $\times 10^6$) to spawning-stock biomass

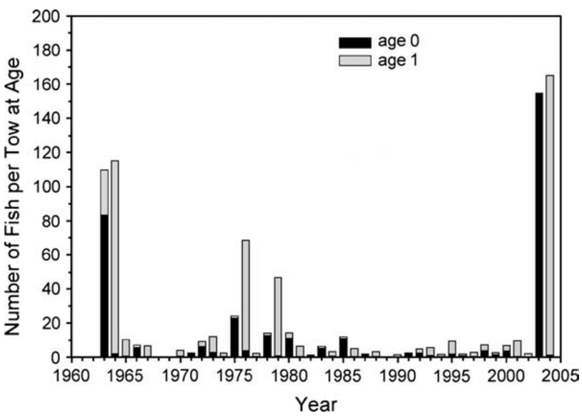

Figure 4. Relative abundance of zero and one-year-old haddock from the Northeast Fisheries Science Center bottom-trawl survey.

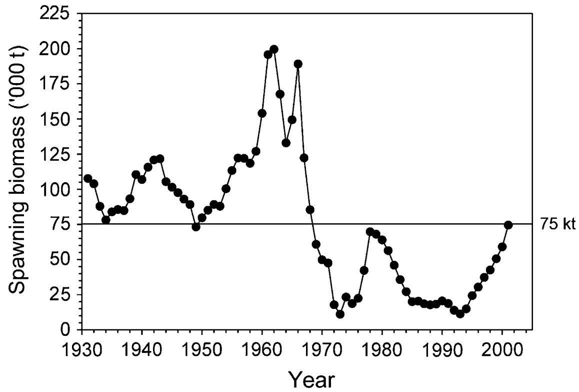

Figure 5. The spawning-stock biomass (SSB) of Georges Bank haddock from 1931 to 2001 based upon VPA analyses. The large year classes of haddock on Georges Bank have different survival rates, as can be seen by comparing the three large year classes and the spawning-stock biomass that produce the large year classes. Referring to Figure 4, it can be seen that the very large SSB in the early-1960s was associated with the large recruitment of 1963. The relatively large year classes in the mid-1970s were associated with relatively low SSBs, and the very large year class of 2003 was likely associated with an intermediate-size year class.

(10^3 MT) or the number of recruits-per-ton of spawning fish ($\times 10^3$) is: 1963, 472/156 = 3; 1975, 103/18 = 5.7; 1978, 84/69 = 1.2; 2003, 900/80 = 11. VPA values for 2003 are not available, so spawning-stock biomass (SSB) and recruitment were estimated based upon available indices.

It appears that haddock spawning-stock biomass has been increasing, on average, since 1995 (Figure 5). So the fact that there was a particularly large year class in 2003 was probably not just the result of an event or complex of events in 2003, but rather a change in improved conditions for haddock immediately after 1995. Because the data set for the 2003 year class is not complete, we believe we can contrast conditions in 1995 (a very poor year) with post-1995 conditions to reflect the nature of the strong environmental signal associated with the very large year class of 2003.

Thus, even within wide margins of error, the apparent early-life-history survival rate for large year classes of haddock varies substantially, suggesting that the generation of large year classes is not the result of a simple, common cause. Density-dependence is an issue that must be considered, and it should be noted that the apparent survival rates for 2003 were exceptionally high, perhaps as much as double the survival rates in 1963.

Temporal distribution of eggs and larvae

Generally, larger spawning stocks will produce larger quantities of eggs (although there are issues involving egg production per female and survivability and quality of eggs). A significant feature of relatively large egg production for any particular stock is that the temporal and spatial extent of egg distribution is increased with large egg production.

The temporal extent of egg production is certainly increased in the case of the haddock. This is exemplified by contrasting the distribution of haddock eggs on Georges Bank between 1995 and 1999 (P. Berrien, pers. comm.) (data are not available for the 2003 year class). The greater temporal and spatial extent of egg production in 1999 is displayed in Figure 6. Apparent survival is higher in 1999, and it is remarkable that the modal numbers of larvae occur later in 1999 than in 1995 (Figure 7).

Distribution of young of year

The distribution of the young-of-the-year fish is different among year classes. Figure 8 shows that, in 1963, the young of the year were concentrated in the Gulf of Maine–Browns Bank–eastern Georges Bank; in 1987 on Nantucket Shoal and Middle Atlantic Bight; and in 2003 on Georges Bank, indicating that not only was survival different, but so was the location of concentrations of young fish. The distribution of 0-group haddock is plotted for the 1975 and 1978 year classes on Georges Bank by Overholtz (1985). From the autumn surveys, both year classes were widely dispersed over Georges Bank with highest abundance in 41–60 m. These two year classes had very high recruitment at age 1. Note that the 1987 year class had average recruitment despite having a high age 0 abundance in the autumn.

Density-dependence

The stock and recruitment data for Georges Bank are plotted in Figure 9. The data appear in standardized deviation units. The figure shows a loess tension = 0.3 smoother curve passing through the standardized recruitment-stock data. In general, stock sizes less than the mean stock size produce relatively poor recruitment (the 1975 year class stands out as an exception). Stock sizes between the mean and ± 1 s.d. produce relatively good recruitment. While stock sizes greater than 1 s.d. produce generally poor recruitment, the 1963 and 1975 year classes stand out as exceptions. Figure 9 raises a question relevant to decision theory, "Should a manager prefer keeping the stock at an average size and obtain, on average, relatively large recruitment; or should a manager prefer to keep the stock large and reduce recruitment on average, but occasionally produce a very large year class?"

Stock structure

The environmental conditions for year class size depend, of course, on stock structure. It has been explicitly assumed that the Georges Bank (NAFO 5Z) haddock stock is separate from the Scotian Shelf–Browns Bank (NAFO 4X) stock. However, the magnitude of normalized recruitment for the three areas appears to be of common magnitude for some time stanzas (Figure 10). VPA recruitment estimates are available for 5Z from 1931 to 1996 and for 4X from 1962 to 1996. There is a coincidence of relatively large recruitment in the early 1960s; the large recruitments in 1975 and 1978 on Georges Bank were consistent with a trend in increased recruitment that occurred in the mid-1970s in 4X; and recruitment began to increase in 4X in the 1990s, leading the increase in 5Z that began in 1976. It appears that, when all of the recent data are assembled, both 4X and 5Z will have experienced large year classes of haddock.

The Georges Bank wind index

Hourly wind direction and velocity data from buoy 44018 located on Georges Bank were transformed into Cartesian coordinates. The mean direction and velocity is deduced from the centroid of the scatter plots in Figure 11. The figure shows that the windforcing was generally from the northwest quadrant. The 50% confidence kernel is used to delineate average and unusual years. Using this criterion, 1987, 1988, 1989, 1995, and 1998 represented unusual wind signals; 1987, 1989, and 1995 were from the northeast, while 1988 and 1998 were from the northwest and southwest, respectively.

The scatter plots can be analysed further by computing the correlation between the east–west points and the north–south points. For the dominant northwest forcing direction, the correlations are very small and have a tendency to be negative, implying that the variation in wind is along the southeast–northwest axis, while data in other quadrants reflect higher positive correlations, implying that wind varies along the southwest–northeast axis.

The variations in interannual differences in scatter of the hourly wind observations, the centroids of the wind observations, and the correlations show that the nature of windforcing is much more complex than just the direction and velocity of the windfield. In particular, the autocorrelation structure of the wind observations, which is beyond the scope of this study, is particularly important, because these autocorrelations and cross correlations specify the short-term persistence of windforcing, which likely varies among years, causing the windstress to vary as well.

Discussion

The main theme of this paper concerns changing our understanding of fish population dynamics from short-term time scales to climate time scales using a decision-theoretic framework to calibrate the level of predictability.

Decision theory provides a framework for evaluating what is known and what is not known about the impact of environmental variables on stock productivity. We have shown that Markov chain formalism can be used to implement the stock component of the decision-theoretic analysis in order to interpret the "state of the stock". However, the full utility of decision theory requires extending

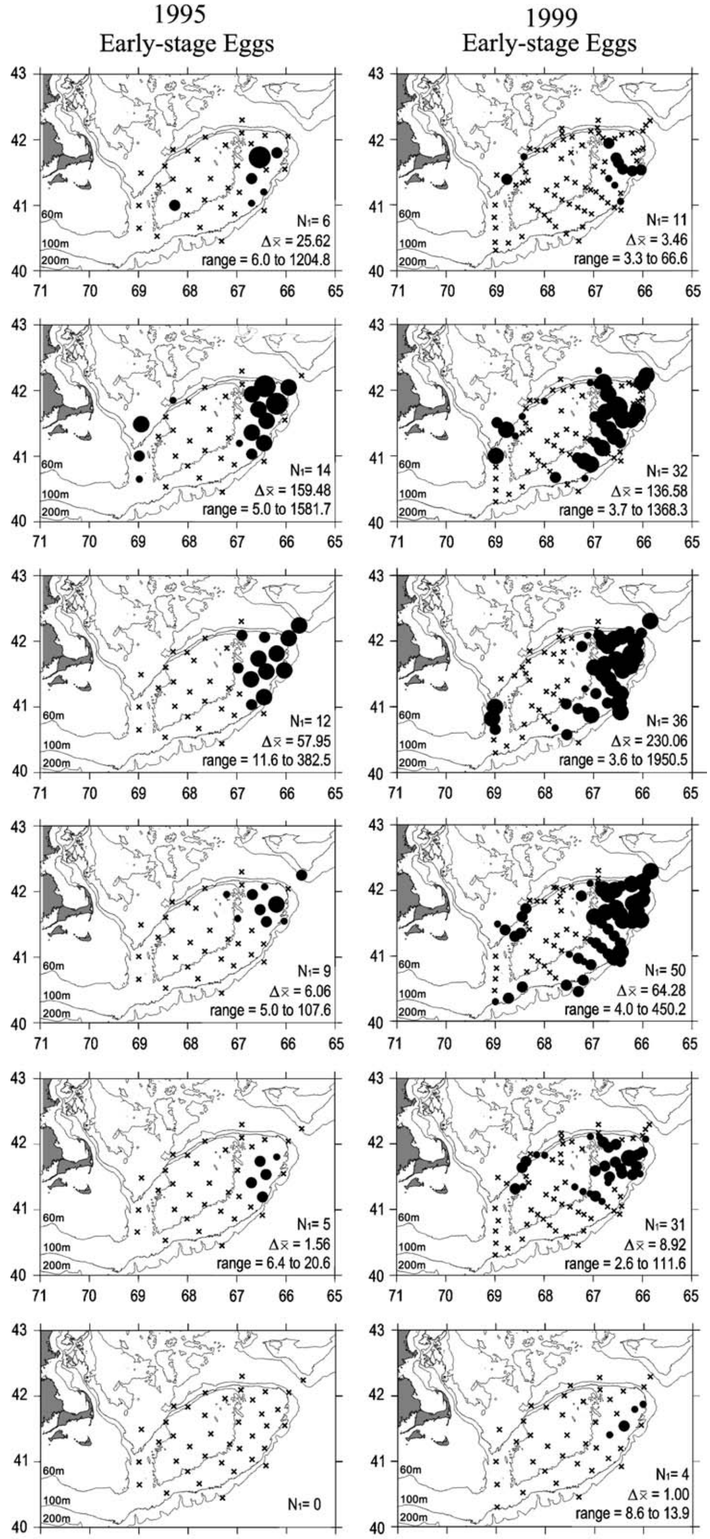

Figure 6. Contrast distribution of early stage haddock on Georges Bank in 1995 and 1999. Top row February and monthly to bottom row July. N is the number of positive observations; Δ is the mean of positive observations. The range is the range of positive observations.

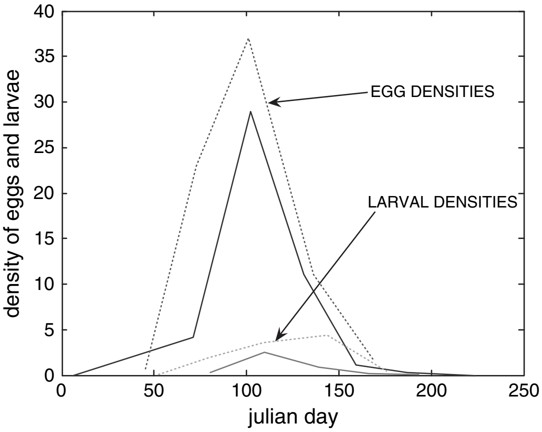

Figure 7. Comparison of haddock egg and larval densities on Georges Bank in 1995 (solid lines) and 1999 (dotted lines). The apparent cumulative survival appears much greater in 1999 than in 1995.

the analysis to take into account specific, environmentally-related conditions.

In its simplest form, this is equivalent to partitioning the states into eight components rather than only four. This partitioning can be accomplished for any specific time scale. However, the issues for a climate-scale partitioning seem less well understood than for contemporary time scales. In making this transition, it seems important to evaluate an eight-component partition for the contemporary time scale. In developing insights into an eight-state partition for recent decades, it seems reasonable to search for a case study with strong environmental signals that might be associated with the several sporadic, large year classes of haddock that have been spawned on Georges Bank during the last half century, under the hypothesis that common environmental factors cause the larger year classes. However, using this as a point of departure to discuss longer-term time scales, it did not appear that the large year classes could be easily linked to environmental factors, because their early-life-history survival rates and distribution seemed to differ significantly. In the course of examining these large year classes, it seemed worthwhile to explore the hypothesis that the character of the windfield influences retention or other features of high survival. However, we found no relation between NAO and the Georges Bank wind index, nor did we find a relation between the Georges Bank index and recruitment.

While the need to take into account short- and long-term environmental variability is obvious, it is not always clear how to accomplish this. The challenges are substantial. For example, the nature of relationships that tie environmental variability and fish population dynamics together are inherently nonlinear. The inherently nonlinear setting means that the trajectory of a fish population and an environmental forcing function can be perfectly correlated with one another, even though the usual linear statistical

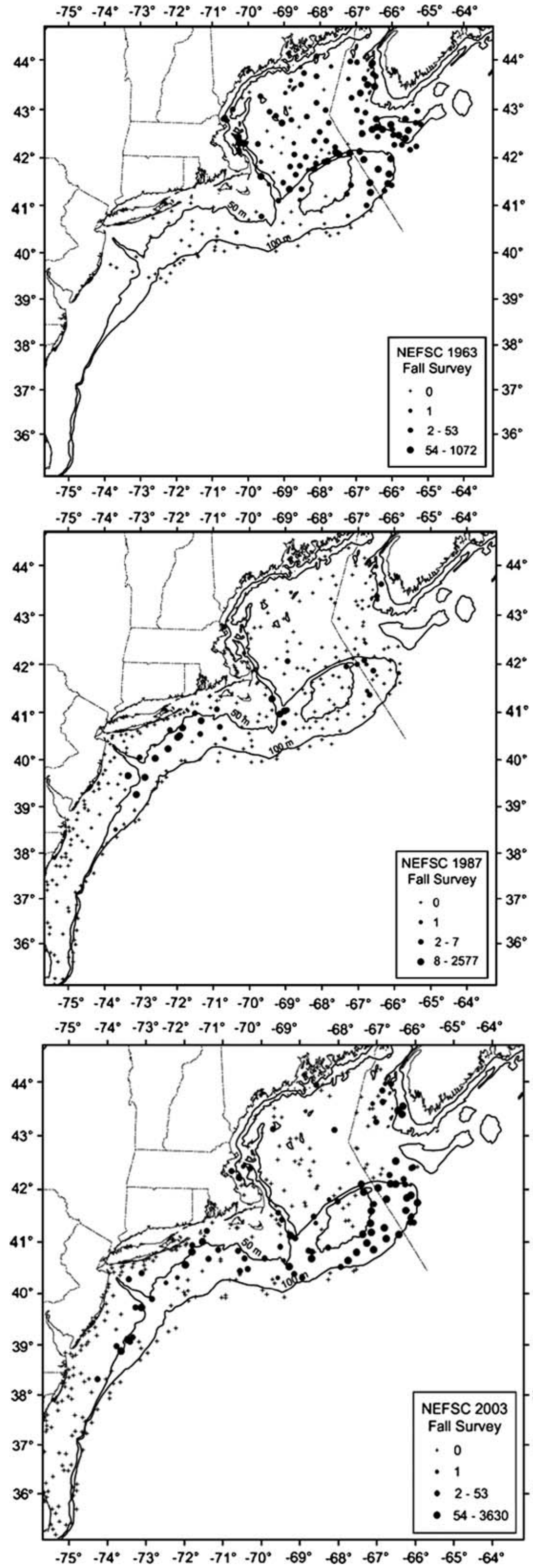

Figure 8. Distribution of young-of-the-year haddock taken in the Northeast Fisheries Science Center fall surveys.

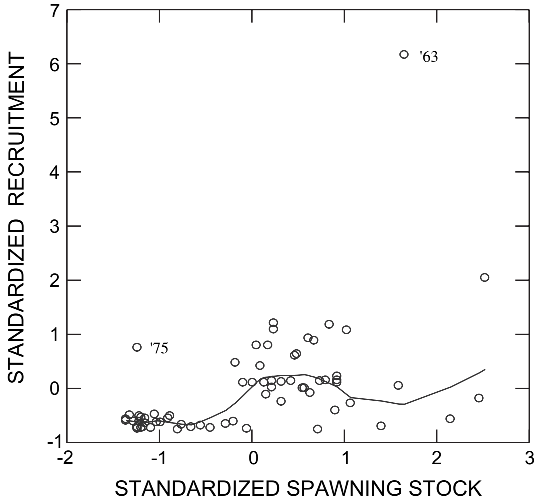

Figure 9. Standardized recruitment plotted against standardized stock in standard deviation units. A loess tension = 0.3 smoother is fitted through the data. When the stock is small, recruitment is generally small. When the stock is an intermediate size, recruitment tends to be relatively large. When the stock is large, recruitment declines on average, but exceptional numbers of recruits can be produced. The relatively large recruitment-spawning stock ratios for 1963 and 1975 are identified.

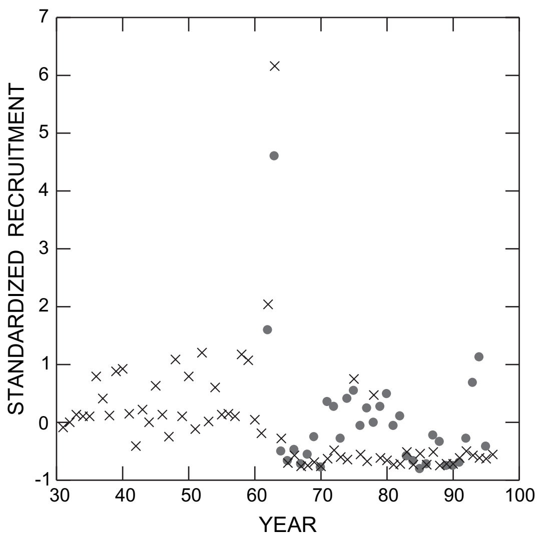

Figure 10. Standardized haddock recruitment of Georges Bank (crosses) and Scotian Shelf—Browns Bank (dots). Note that large recruitments occur in both regions in the early 1960s. There is a clear increase in recruitment on Scotian Shelf—Browns Bank in the 1970s. There are intriguingly few relatively large year classes on Georges Bank during this period. The standardized recruitment is beginning to increase in the mid-1990s on the Scotian Shelf—Browns Bank. Recent data show that both areas have high production of haddock in the early 2000s.

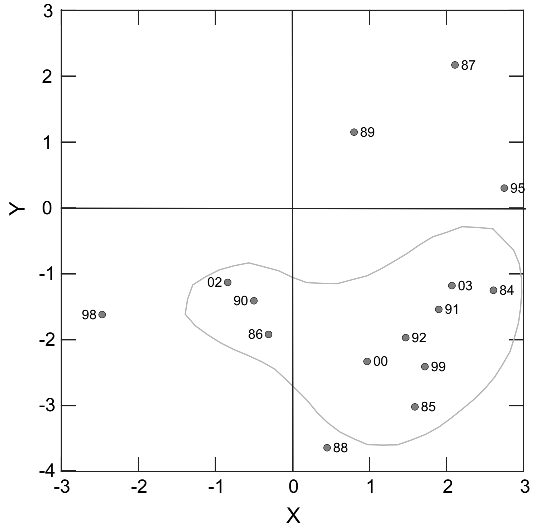

Figure 11. Centroid of March wind velocity and direction plotted in Cartesian coordinates by year. Following mathematical convention, the point (3, 0) is north; the point (0, 3) is east; etc.

correlation statistic is close to zero. In contrast, under the conventional, usually implicit assumption of linearity, highly correlated variables may not be causally related.

A second challenge, particularly relevant to this Symposium, is that environmental effects are evoked on multiple times and space scales (Rothschild, 2005). In the simplest terms, the relationship among fish stocks and environmental variables may be very different on climate time scale than from shorter-term time scales conventionally used in fish stock analysis. For the same variable (e.g. wind velocity or temperature), causal relationships might only exist at certain frequencies or wave numbers. Identifying which scales are important or critical is complicated even with apparently "easy" variables such as temperature. It is obviously easier to examine relatively short time windows of fish stock—environmental relationships simply because of the availability of data. How does short-term, high-frequency variability translate to longer-term and lower frequency variability, and *vice versa*? What is the relation between annual—decadal scales and climate scales?

A third challenge is the difficulty in resolving critical levels of mortality rate. For example, a generally undetectable plus or minus change in early-life-history mortality rate of highly fecund fish can generate variations in year class strength that are greater than those actually observed (Jones, 1973; Beyer, 1989; Rothschild, 2000). Many reported linkages between fish stock abundance and the environment are based on variations on early-life-history mortality perturbations that far exceed the level necessary to generate unobserved, explosive increases or decreases in year class strength.

A fourth challenge involves the need to shorten the length of the causal chain. The NAO is a good example. As a "cause", its effect in the western Atlantic is certainly related to multiple factors such as, for example, the position of the Gulf Stream wall and the windfield over Georges Bank (Taylor and Stephens, 1998). At the same time, the "effect" that we are interested in explaining is not homogeneous in an obvious way, as demonstrated by the haddock analyses. Different large year classes of haddock result from very different early-life-history survival rates. This suggests that each large year class is driven by different causes. It is reasonable to assume that greater insights might be obtained by examining the interrelationships of turbulent, small-scale flow and fish larval feeding success, for example, than imagining that there is some simple linear relationship linking the NAO with the recruitment success of many species of fish.

The analysis of the relatively large recruitment years for Georges Bank haddock was quite useful in the sense that it generated a scenario of the causes of large year classes of haddock and apparently important research areas. The varying survival among years of high recruitment reflects years of varying productivity for young haddock. The intermittent, large recruitments seem typical of haddock populations both on Georges Bank and in the North Sea.

The fact that there are interesting correspondences between normalized recruitment on Georges Bank (5Z) and Scotian Shelf—Browns Bank (4Z) suggests that the conventional statistical boundaries might not separate unit stocks, or that the stocks are under common environmental control. This suggests that the haddock on Georges Bank and Browns Bank could be a single stock or multiple stocks under common environmental control.

Three hypotheses arise:

(i) As the haddock population increases in abundance, its distribution spreads. This concept is consonant with the fact that, in many examples, exploding stocks increase their range rather than abundance at the core of their range (Rothschild, 2000). This suggests that stock separation is not consistent with NAFO boundaries and that haddock on Georges Bank share common properties with those on Browns Bank and the Scotian Shelf.

(ii) Internal variability in the numbers of larvae on Georges Bank or the survival of larvae on Georges Bank arises from the origin of the flow onto Georges Bank. In other words, the notion of retention, which is associated with particles leaving the Bank, gives only part of the picture—the character of the inflow may be more important than the outflow.

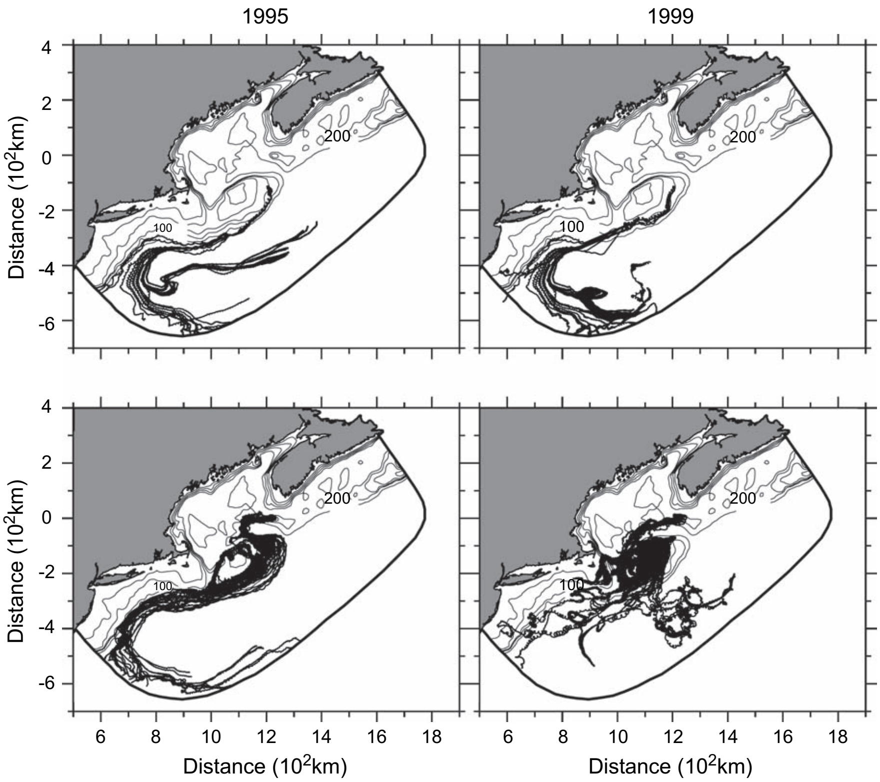

Figure 12. Trajectories of fluid particles. Particles are released near the surface on the northeastern flank of Georges Bank (upper) and Browns Bank (lower) on 15 February and tracked until 30 June for both 1995 and 1999. While the Georges Bank releases tend to be similar in 1995 and 1999, the residence time of particles for particles originating on Browns Bank seems to be longer in 1999 than in 1995.

(iii) The productivity of Georges Bank is under regional control, associated at least some of the time with the character of the flow onto Georges Bank. This is consistent with the suggestion that improved environmental conditions generated improved haddock recruitment in 1999 when contrasted with 1995, as reported by Platt *et al.* (2003) for Scotian Shelf haddock.

To exemplify the issue of the flow onto Georges Bank, we have compared the influence of local windforcing using the Gulf of Maine–Georges Bank mesoscale meteorological model, MM5, to drive the Lagrangian tracks of particles in the FVCOM model (Chen *et al.*, 2003, 2005). Particle tracks were seeded in February for Browns Bank and Georges Bank. The years 1995, a poor year for haddock recruitment, and 1999, a good year for haddock recruitment, are compared in Figure 12. (Unfortunately, model output for 2003 was not available for this paper.) Figure 12 shows that windstresses interacting with the internal dynamics gave a very different flowfield in 1995 and 1999, suggesting a greater mixing and slower through-flow in 1999 than in 1995. Although any conclusions are preliminary, a longer residence time on Georges Bank in 1999 is consistent with Figure 7.

Fortunately, new modelling capability will enable us to resolve the interannual variability in windforcing the flowfield and other physical and biological properties for the region. It seems that an important next step is to examine the windfield directly over Georges Bank. An index of interannual wind velocity does not show an obvious correlation with either the changes in haddock productivity on Georges Bank or the NAO (see e.g. Drinkwater *et al.*, 2003). It is now feasible to examine this problem because of the availability of past mesoscale windfield data reproduced by the fifth generation mesoscale meteorological model (MM5) (Chen *et al.*, 2005) and the unstructured grid finite-volume Gulf of Maine–Georges Bank circulation model based on FVCOM (Chen *et al.*, 2003). It continues to appear that understanding processes on short time scales is important in understanding how they are integrated at climate scales.

In conclusion, the decision-theoretic approach provides a very clear specification of the information gaps that must be filled to improve management. The improvements in our understanding of short time scales are echoed as the problem is shifted to longer time scales. It is clear that, to improve climate-scale inferences, a better understanding of smaller scale processes will likely be needed. A promising approach involves the more detailed analysis of Lagrangian tracks. The more detailed examination needs to include specifics of high frequency and interannual windforcing from the physics side (see Lough *et al.*, 1994; Brickman, 2003;) and an evaluation of density-dependence (see Heath and Gallego, 1997).

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