AN INITIAL INVESTIGATION OF AN APPROACH TO DEVELOP A SURVEY-BASED RULE TO JUDGE WHETHER ABUNDANCE HAS DROPPED BELOW AN APPROPRIATE "LIMIT REFERENCE POINT" FOR ATLANTIC MENHADEN

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ABSTRACT

Two aspects of the specification of an abundance-based Limit Reference Point (LRP) for the Atlantic menhaden fishery are investigated: the choice of an appropriate value for such a LRP, and the associated operationalisation of such a choice by means of a simple decision rule, based on the JAI survey index, to decide whether or not the resource has dropped below that LRP. Possible choices for such an LRP in terms of the population fecundity (*FEC*) index are motivated on the basis of the current assessment of the recent dynamics of the resource. Projection-simulation methodology is developed to test an associated class of decision rules across a range of scenarios spanning various assumptions for future catches and recruitment levels. A specific rule: that if the average value of the most recent two available JAI annual survey results is below 13, then resource abundance be considered to have fallen below the LRP, is argued to show robust performance over both the range of scenarios for future catches and recruitments, and the range put forward for a *FEC*-based LRP. Some suggestions for possible extensions of this initial investigation are made.

INTRODUCTION

The matter of the specification of biological reference points for the fishery for Atlantic menhaden (*Brevoortia tyrannus*) has recently been raised. Potentially the most important of these would seem to be the LRPs (Limit Reference Points). Though interpretation of LRPs varies across the globe, most generally the concept to which they are closely linked is an abundance level below which the probability of continuing reasonable levels of recruitment may be impaired. Hence if abundance falls below that level, consideration should be given to imposing or strengthening existing management restrictions. Whatever that level might be, the relative stability of the Atlantic menhaden fishery over the last some 25 years suggests that it is probably unlikely to have been breached. Thus, in specifying an LRP for the resource, and particularly one expressed not too abstractly, but rather in terms that allow ready comparison with data from the regular monitoring of the resource, the aim should be to identify circumstances that reflect a high probability that the reproductive component of the resource is being maintained within the range over which it has fluctuated during the past quarter-century.

Although the fishery for Atlantic menhaden lands relatively high catches in tonnage terms each year, the data available to assess the resource are limited. In any assessment the information of greatest importance is almost always the time-series of indices of abundance. For menhaden, of two indices available, that from the PRFC pound net fishery pertains to such a small component of the fishery that it would not *a priori* be expected to be particularly reliable – indeed these data do not fit the current Beaufort Assessment Model (BAM) (ASMFC 2010) at all well over recent decades. The index of recruitment (juvenile abundance index - JAI) provided by the state-specific seine surveys would also not be expected to be highly reliable, particularly because these surveys were not designed for the menhaden resource, and their fit by the BAM over the period from 1960-2008 is poor in the earlier years. However from the mid-1980s onwards these survey estimates of recruitment **are** reasonably fitted by the model, and they have the added advantage of being fishery-independent. The BAM based assessments also support what is suggested by the relative stability of the fishery over the last 25 years: that following a period of enhanced recruitment from the mid-1970s to mid-

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1980s as a result, presumably, of a favourable environmental regime, the resource has fluctuated about a reasonably steady level of abundance.

The purpose of this paper is to report initial investigations of an approach, based on the considerations above, to:

i) specify possible choices for an appropriate abundance-related LRP for the Atlantic menhaden fishery; and
ii) operationalise such a choice by means of a simple decision rule, based on readily available resource monitoring data, to decide whether or not the resource has dropped below such a LRP.

The paper first sets out the projection-simulation methodology required for this approach, and proposes summary statistics for use in evaluating the results. A range of scenarios spanning alternative assumptions for future catches and recruitments is developed, and the performance of a simple class of decision rules, based on the JAI survey index, as to whether or not the population has fallen below a suggested LRP is evaluated. Based on this, a specific rule which demonstrates robust performance across the scenarios developed is selected. Its performance is evaluated over a range of possible choices for an LRP, where the specification of this range is motivated by reference to the assessed behaviour of the resource since 1985.

METHODS

The approach requires projection of menhaden catches and resultant population size (in the form of a numbers-at-age vector) into the future. This involves a number of steps whose mathematical details are provided in the Appendix.

For some of these steps, alternatives options are put forward, so that overall a number of different projection scenarios are considered. These steps, together with some rationale for the alternatives considered, are as follows.

<u>Step 2</u>: Catch

A novel feature of this situation is that as there are no formal restrictions on the annual take of menhaden, the modelling required has to incorporate an approach to specify future catches as well as to address the customary need to specify how to compute future population trends. The two major contributors to the menhaden catch are the reduction fishery and the bait fishery, with the trends in their sizes since 1986 shown in Fig. 1. While these plots might suggest a slight increasing trend over time in the bait fishery, the bait catch of menhaden is so much smaller than its reduction fishery counterpart that there seems no need to introduce particular sophistication in modelling its future levels, which have consequently been determined by random sampling with replacement from past values over 1986-2008.

There is however a much stronger indication of a trend (a decrease in this instance) in the larger reduction fishery catches since 1986 (see Fig. 1). Thus in addition to considering future catches from the reduction fishery as sampled at random from the 1986-2008 period, a further scenario which assumes that it is the more recent (2004-2008) lower levels that are likely to be indicative of what to expect in the future is also considered. In all cases, the catch selected carries with it the selectivity pattern with age that applied to that catch in the year it was made previously. Thus we consider the following.

a. Future catches and selectivity for the reduction fishery are sampled randomly (with replacement) from the past values for the period 1986-2008.

b. Future catches and selectivity for the reduction fishery are sampled randomly (with replacement) from the past values for the period 2004-2008.

Some limited checks were made as to whether there were any other of the data available that could be used for predicting future reduction fishery catches. Correlations of annual reduction catches are evident with both the recruitment survey index of the year and with the previous year's catch. However when these effects are estimated jointly, the magnitude of the former is minimal, so that the options considered to take such effects into account include only first order autocorrelation with the previous year's catch. Options corresponding to the same two periods from which past recruitment is re-sampled are considered. However since the autocorrelation for the shorter 2004-2008 series is (somewhat surprisingly) negative, a further option was added which uses the autocorrelation estimate for the whole period to apply to projections based on the 2004-2008 reduction catches. For these options, the selectivity at age vector is selected at random with replacement from vectors for the associated past period considered. Thus we consider also the following.

c. First order autocorrelation in the reduction catches, with the autocorrelation and variance parameters estimated for the 1986-2008 period.

d. First order autocorrelation in the reduction catches, with the autocorrelation and variance parameters estimated for the 2004-2008 period.

e. First order autocorrelation in the reduction catches, with the variance parameter estimated for the 2004-2008 period and the autocorrelation parameter for the 1986-2008 period.

Step 4: Recruitment

There is little indication of any relationship between recruitment and reproductive capability (measured by population fecundity *FEC* – see equation A15) over the 1986-2008 period. Therefore the first option considered was to assume that the future recruitment varies randomly about its average value over this period, where this average and the variability about it (measured by σ_R – see equation A14 – equal for this option to 0.35) is as estimated from the BAM assessment results.

a. Geometric average recruitment over 1986-2008, no autocorrelation in the residuals.

However, under that option, future recruitment levels are not compromised if harvests reduce egg production to low levels. To allow for that in a way that also factors in the absence of any firm evidence that recruitment success has been lowered since 1986 for this reason, two options with alternative stock-recruitment relationships have also been considered.

b. Hockey-stick with the relationship changing from a straight line through the origin to a constant level (see equation A11) above a "FEC_{hinge}" value of about 9 million mt (for this option this is the minimum *FEC* value estimated over the 1986-2008 period in the BAM assessment), no autocorrelation in the residuals.

c. Hockey-stick as in **b**, but with the value of FEC_{hinge} raised to 15 million mt, corresponding roughly to a cluster of *FEC* values in the stock-recruitment plot immediately above the minimum value of *FEC*; no autocorrelation in the residuals.

None of the three options above take account of possible temporal autocorrelation in the residuals about the stock-recruitment relation estimated. The final option adds this effect (estimated – see equation A13 - at ρ = 0.81) to c above, with **c** being the option chosen for this addition as it is the most challenging of these first three options from a resource risk standpoint.

d. Hockey-stick as in **b**, and with the value of FEC_{hinge} raised to 15 million mt, but now also with autocorrelation in the residuals.

Finally at Step 5, observation error with a standard deviation equal to that evident in the past (σ – see equation A19 – which is estimated here to be σ = 0.17) is added to the recruitment generated for the year to extend the *JAI* survey index series into the future. This is followed by application of the decision rule at Step 6 to decide on the basis of these *JAI* values whether *FEC* is considered to have fallen below the specified LRP.

In measuring how well a decision rule under consideration is performing, one wants a statistic summarising how frequently the rule "gets it right", i.e. how frequently it identifies that *FEC* is indeed below the LRP specified, and also how frequently it is correct in the reverse situation (identifying that *FEC* is above the LRP when this is case in reality) as a large proportion of "false positive" identifications of the resource as below the LRP when this is not the case would not be desirable from the perspective of an efficient resource utilisation approach. However, simply using the proportion of times such events occur in 100 replications of the application of the rule over a 20-year projection period has the problem of a lack of comparability across the various scenarios (each scenario is a combination from the options elaborated above), because *FEC* falls below the LRP specified for different proportions of the time for the various scenarios. Performance statistics have thus been normalised to the number of times that *FEC* fell above or fell below the LRP specified under a particular scenario. Thus four probabilities are calculated.

P1 - the probability that the decision rule is correct in identifying that *FEC* is below the LRP (i.e. a probability conditional on *FEC* being below the LRP specified);

P2 - the probability that the decision rule is correct in identifying that *FEC* is at or above the LRP;

P3 - the probability that the decision rule is incorrect in identifying that *FEC* is below the LRP; and

P4 - the probability that the decision rule is incorrect in identifying that *FEC* is at or above the LRP.

For a measure of success that can be considered equivalent across the scenarios, one seeks a rule that maximises the sum of P1 and P2. This avoids anomalies where, for example, for a scenario for which *FEC* seldom falls below the LRP specified, the decision rule can appear very successful because by setting its threshold high, it makes few mistakes in that respect (but this is at the expense of a large number of false positives).

The class of decision rules considered is detailed in Step 6 of the Appendix. Essentially the decision depends on whether or not the value of *FEC* averaged over *t* recent years has fallen below a threshold level *X*. The probabilities above are computed for a range of choices for the decision rule parameters *X* and *t,* with the objective being to choose *X* and *t* so as to maximize the measure P1+P2 that the rule is correct. Three different choices for the LRP are considered: 10, 12.5 and 15 million mt for *FEC*.. The first and last of these correspond closely to the values of *FEC* for the lowest and set of next lowest *FEC* values occurring since 1986 in terms of the BAM assessment. The appropriateness of such a range of choices for an LRP is discussed further below.

Overall 20 scenarios are examined, comprising all 5x4 combinations of the options described in steps 2 and 4 above. These scenarios (A to T) are described in Table 1.

RESULTS

An example of some actual trajectory realisations ("worm plots") of future recruitment, JAI, population fecundity *FEC* and catches (for reduction and bait fisheries separately) is shown in Fig. 1 for scenario A, together with medians and 95% probability envelopes. Note that the medians and upper and lower 2.5%iles are not true trajectories but rather lines joining percentiles of the distributions of the various statistics for each future year.

In Fig. 2, these medians and 95% PI envelopes (except for the less important bait catches) are compared for each of the 20 scenarios, and shown together with the stock-recruitment relationships assumed for each.

For each of the 20 scenarios and LRP choice, a specific rule (*X* and *t*) is chosen to maximize P1+P2. The process used for this is illustrated in Fig. 2, which gives full results for different decision rule options (different values for *X* and *t*) for scenario A. The selected rule and the resulting probabilities are compared in Table 3 across the 20 scenarios A-T.

Based on these results, our recommendation for robust performance would be to choose *X*=13 and *t*=1 as the operational decision rule. This rule thus states:

> ***Calculate the average value of the JAI survey index for 2 and for 3 years before the current year; if this value is below 13[3], conclude that FEC next year will fall below its LRP.***

Table 4 gives the results for this choice for the rule for each scenario and LRP choice. Fig. 3 compares the results for the chosen rule and the optimal (i.e. Table 3 choice) rule for each combination of scenario and LRP choice.

[3] JAI as utilised here (Table A8) is a relative index which is output from a GLM procedure (ASMFC 2010). Updates of a GLM given further data can change the scale of the index. In any future application then, for comparability over time, the updated index could be normalised by its average value from 1986 to 2008 only, and comparison in the rule made to the value of 13 adjusted by a similar normalisation except rather to the average over 1986-2008 of the values given in Table A8.

DISCUSSION

The concept of an LRP is often linked to some abundance level below which the probability of reasonable levels of recruitment may be impaired. Thus, for example, the Marine Stewardship Council's (MSC's) recent guidance to certification bodies speaks of "the stock status at which there is an appreciable risk that recruitment is impaired" in this context (MSC 2009).

The basis for suggesting above a LRP for *FEC* in the range of 10 to 15 million mt is linked to this concept, together with its operational corollary that an LRP can be motivated as the lowest level of the reproductive capability of a resource at which the population has shown an ability to recover following preceding reduction. In this case the resource did increase following *FEC* dropping to some 9 million mt in 1992, which is the basis for the lower end of the range suggested above. However, considering only the corresponding single point on the stock-recruitment plot does not guarantee a high probability of reasonable recruitment at that level of *FEC*, so that there is a need to also consider higher possible choices. The higher end of the range suggested is motivated by the stock-recruitment plots in Fig. 2, which indicate a number of cases of higher than average recruitment achieved for *FEC* values in the vicinity of 15 million mt.

Fig. 2 includes 20-year projections of *FEC* under the various future catch and resource dynamics scenarios considered. In median terms these increase for scenarios with lower future reduction fishery catches (based on the more recent 2004-2008 period). This is except for the more-pessimistic stock-recruitment relationship option **c** for which the hockey-stick model suggests lower recruitments for *FEC* < 15 million mt (scenarios L, N and O); for these the median *FEC* values fluctuate close to the lower end of the range suggested for a *FEC*–based LRP. Broadly speaking, for scenarios with higher future reduction catches based upon the 1986-2008 period, median *FEC* trends are close to one or other ends of the suggested *FEC*-based LRP range.

The projected lower probability envelopes for *FEC* are slightly below the lower limit of the suggested *FEC*-based LRP range for scenarios A-J, but seem really problematic only for the K-T scenarios with their more pessimistic FEC_{hinge} choice for the hockey stick stock-recruitment relationship, as for those the lower limits of the probability envelopes show a continuing downward trend over time.

However, for the purposes of this analysis, the concern is not so much about what could happen in terms of falling *FEC* values, but rather about how good a decision rule can be developed to ascertain whether *FEC* has dropped below such an LRP. The intended norm associated with LRP's is that some corrective management action would then be taken.

The results in Tables 3 and 4 show that the decision rule control parameter choice of *X*=13, *t* =1 shows surprisingly robust performance across not only the 20 different projection scenarios, but also for the alternative choices put forward for the LRP of *FEC*=10, 12.5 and 15 million mt. Generally the P1+P2 measure of "rightness" of the rule is improved only slightly in some cases by moving to *t*=0 in conjunction with a lower value of *X*. Fig. 3 provides perhaps the readiest means of assessing the robustness of this choice, which for practical purposes is optimal except for scenarios incorporating the more pessimistic hockey stick stock recruitment relationship, and only weakly sub-optimal for those, in terms of P1+P2. Indeed, from a resource risk perspective, the chance of a false negative when *FEC* is below the LRP (P3) actually improves with the move from the scenario-specific optimum in terms of P1+P2 to the *X*=13, *t* =1 choice, except in the case of the highest choice for the LRP in conjunction with scenarios P-T (more pessimistic stock recruitment relationship together with autocorrelation in recruitment residuals).

Note that for a decision in a current year in regard to the likely level of *FEC* for the following year, and hence possible management action for the fishery for that year, the *X*=13, *t* =1 rule requires values of JAI for two and three years earlier. In practical terms, such a rule would be implemented using the most recent two JAI indices available at the time any decision was to be made. In that context then, if for the current year the value of JAI can become known for the previous, or even better for the current year, effectively advance notice can (if pertinent) be given of likely problems ahead, so that there is the opportunity to effect possible remedial management action in good time with improved consequences for the resource, and hence also for the fishery in the longer term.

Possible future work

There are directions in which these initial analyses might be expanded. For example, the decision rule might be based on an updated assessment, rather than the simple empirical approach based on the JAI survey index considered here. Practical computation time limitations would likely preclude simulation testing of an assessment approach as complex as the BAM, but the use of simpler population models might be investigated.

Probably of more import and likely benefit would be extending the scenarios considered here to take account of both the level of estimation precision of the base BAM assessment, as well as the more influential of the changes to the assumptions of that base case considered in ASMFC (2010). Further functional form assumptions for the stock recruitment relationship might also be considered. In a somewhat different context, this approach could also be of value in assessing the cost-benefit of the development of a fishery-independent index of the abundance of the older menhaden age-groups, as might for example be provided by a regular aerial survey.

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Table 1: Scenarios investigated

	Stock-recruitment relationship	Reduction Catch
A	av (1986-2008), no autocorrelation	random (1986-2008)
B	av (1986-2008), no autocorrelation	random (2004-2008)
C	av (1986-2008), no autocorrelation	with autocorrelation (1986-2008)
D	av (1986-2008), no autocorrelation	with autocorrelation (2004-2008)
E	av (1986-2008), no autocorrelation	with autocorrelation (2004-2008)*
F	Hockey-stick (min), no autocorrelation	random (1986-2008)
G	Hockey-stick (min), no autocorrelation	random (2004-2008)
H	Hockey-stick (min), no autocorrelation	with autocorrelation (1986-2008)
I	Hockey-stick (min), no autocorrelation	with autocorrelation (2004-2008)
J	Hockey-stick (min), no autocorrelation	with autocorrelation (2004-2008)*
K	Hockey-stick (15), no autocorrelation	random (1986-2008)
L	Hockey-stick (15), no autocorrelation	random (2004-2008)
M	Hockey-stick (15), no autocorrelation	with autocorrelation (1986-2008)
N	Hockey-stick (15), no autocorrelation	with autocorrelation (2004-2008)
O	Hockey-stick (15), no autocorrelation	with autocorrelation (2004-2008)*
P	Hockey-stick (15) with autocorrelation	random (1986-2008)
Q	Hockey-stick (15) with autocorrelation	random (2004-2008)
R	Hockey-stick (15) with autocorrelation	with autocorrelation (1986-2008)
S	Hockey-stick (15) with autocorrelation	with autocorrelation (2004-2008)
T	Hockey-stick (15) with autocorrelation	with autocorrelation (2004-2008)*

* the *b* parameter estimated from the 1986-2008 period is used.

Table 2: Full set of results for scenario A. Shading indicates the range of control parameter value (X and t) choices for which the rule is optimal in terms of P1, P2 and P1+P2; the values for P3 and P4 corresponding to the optimal P1+P2 are then also shown.

Proportion above each LRP

LRP	10	12.5	15
	0.82	0.67	0.55

P1: probability rule correct when FEC<LRP

	Rule 1: t=0			Rule 2: t=1			Rule 3: t=2			Rule 4: t=3			Rule 5: t=4		
XX	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
5	0.15	0.17	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.22	0.24	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.47	0.45	0.40	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.54	0.56	0.51	0.05	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.60	0.63	0.61	0.09	0.08	0.06	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.64	0.70	0.68	0.13	0.13	0.13	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00
11	0.67	0.75	0.75	0.46	0.36	0.32	0.04	0.04	0.04	0.02	0.02	0.01	0.00	0.00	0.00
12	0.70	0.78	0.79	0.52	0.44	0.40	0.26	0.22	0.20	0.05	0.05	0.04	0.01	0.01	0.01
13	0.98	0.95	0.92	0.75	0.64	0.58	0.34	0.30	0.28	0.09	0.10	0.09	0.04	0.04	0.03
14	0.99	0.97	0.94	0.81	0.72	0.67	0.39	0.37	0.36	0.16	0.17	0.17	0.08	0.09	0.08
15	0.99	0.98	0.96	0.85	0.77	0.73	0.46	0.47	0.46	0.21	0.23	0.25	0.12	0.13	0.14
16	0.99	0.99	0.98	0.87	0.80	0.78	0.51	0.55	0.54	0.26	0.31	0.33	0.17	0.19	0.21
17	1.00	0.99	0.99	0.97	0.94	0.92	0.57	0.60	0.60	0.33	0.38	0.41	0.24	0.28	0.30
18	1.00	1.00	0.99	0.98	0.97	0.95	0.67	0.77	0.77	0.54	0.58	0.59	0.49	0.50	0.50
19	1.00	1.00	0.99	0.99	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.87	0.55	0.60	0.61
20	1.00	1.00	1.00	0.99	0.98	0.98	0.96	0.96	0.95	0.97	0.94	0.92	0.94	0.92	0.88
25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	0.99	1.00	0.99	0.99
30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
35	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

P3: probability rule incorrect when FEC<LRP

	Rule 1: t=0			Rule 2: t=1			Rule 3: t=2			Rule 4: t=3			Rule 5: t=4		
XX	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
5															
6															
7	0.53														
8		0.44													
9			0.39												
10															
11															
12															
13				0.25	0.36	0.42									
14															
15															
16															
17															
18															
19							0.05	0.06	0.07	0.08	0.09	0.13			
20													0.06	0.08	0.12
25															
30															
35															
40															

P2: probability rule correct when FEC>=LRP

	Rule 1: t=0			Rule 2: t=1			Rule 3: t=2			Rule 4: t=3			Rule 5: t=4		
XX	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
5	0.95	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	0.93	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	0.86	0.92	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	0.77	0.85	0.90	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
9	0.68	0.76	0.83	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	0.59	0.67	0.74	0.93	0.95	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
11	0.48	0.55	0.62	0.88	0.91	0.94	0.98	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
12	0.40	0.46	0.52	0.81	0.84	0.87	0.92	0.94	0.96	0.98	0.99	0.99	1.00	1.00	1.00
13	0.32	0.38	0.43	0.71	0.76	0.80	0.88	0.91	0.93	0.95	0.96	0.97	0.98	0.99	0.99
14	0.26	0.30	0.34	0.60	0.65	0.70	0.80	0.83	0.87	0.89	0.91	0.93	0.95	0.96	0.97
15	0.19	0.23	0.26	0.51	0.55	0.60	0.70	0.74	0.78	0.83	0.85	0.88	0.91	0.92	0.94
16	0.14	0.17	0.20	0.43	0.46	0.50	0.59	0.63	0.67	0.74	0.76	0.79	0.83	0.84	0.87
17	0.11	0.13	0.15	0.30	0.35	0.40	0.50	0.54	0.57	0.63	0.65	0.68	0.74	0.75	0.77
18	0.08	0.10	0.11	0.22	0.26	0.30	0.35	0.40	0.45	0.50	0.53	0.56	0.60	0.63	0.66
19	0.07	0.08	0.09	0.17	0.20	0.23	0.27	0.31	0.35	0.34	0.39	0.43	0.46	0.48	0.51
20	0.05	0.06	0.07	0.12	0.14	0.16	0.19	0.22	0.25	0.26	0.30	0.33	0.31	0.35	0.39
25	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.04	0.05	0.04	0.05	0.05	0.04	0.05	0.06
30	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	0.00	[illegible]	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

P4: probability rule incorrect when FEC>=LRP

	Rule 1: t=0			Rule 2: t=1			Rule 3: t=2			Rule 4: t=3			Rule 5: t=4		
XX	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
5															
6															
7	0.14														
8		0.15													
9			0.17												
10															
11															
12															
13				0.29	0.24	0.20									
14															
15															
16															
17															
18															
19							0.73	0.69	0.65	0.66	0.61	0.57			
20													0.69	0.65	0.61
25															
30															
35															
40															

P1+P2

	Rule 1: t=0			Rule 2: t=1			Rule 3: t=2			Rule 4: t=3			Rule 5: t=4		
XX	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
5	1.10	1.16	1.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	1.15	1.21	1.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	1.33	1.37	1.36	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	1.31	1.40	1.41	1.04	1.03	1.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
9	1.28	1.39	1.43	1.06	1.06	1.05	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.23	1.37	1.42	1.07	1.08	1.09	1.02	1.02	1.01	1.00	1.00	1.00	1.00	1.00	1.00
11	1.15	1.30	1.37	1.35	1.27	1.26	1.02	1.02	1.03	1.02	1.02	1.01	1.00	1.00	1.00
12	1.09	1.24	1.30	1.33	1.27	1.28	1.19	1.17	1.16	1.03	1.03	1.04	1.01	1.01	1.00
13	1.31	1.33	1.35	1.46	1.39	1.39	1.22	1.21	1.21	1.04	1.06	1.07	1.02	1.02	1.02
14	1.24	1.27	1.28	1.41	1.37	1.36	1.19	1.21	1.23	1.05	1.08	1.11	1.04	1.05	1.06
15	1.18	1.21	1.22	1.36	1.32	1.33	1.16	1.21	1.24	1.04	1.09	1.13	1.03	1.05	1.08
16	1.14	1.16	1.18	1.30	1.27	1.28	1.11	1.18	1.21	1.00	1.07	1.12	1.01	1.04	1.08
17	1.11	1.13	1.14	1.27	1.29	1.32	1.07	1.14	1.17	0.96	1.04	1.09	0.98	1.03	1.07
18	1.08	1.09	1.11	1.20	1.23	1.25	1.02	1.17	1.22	1.04	1.11	1.14	1.09	1.14	1.16
19	1.07	1.08	1.09	1.16	1.17	1.19	1.22	1.25	1.28	1.26	1.30	1.30	1.01	1.08	1.12
20	1.05	1.06	1.07	1.11	1.12	1.14	1.15	1.18	1.20	1.22	1.24	1.25	1.25	1.27	1.27
25	1.01	1.01	1.01	1.02	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.05
30	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00
35	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 3: Summary results for scenarios A-T, where decision rule parameters *X* and *t* are chosen to maximize P1+P2.

	A			B			C			D			E		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.82	0.67	0.55	0.86	0.74	0.65	0.82	0.66	0.53	0.85	0.74	0.65	0.87	0.78	0.71
X	13	8	9	13	13	13	13	8	9	13	13	13	13	13	13
t	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
P1: FEC<LRP, rule correct	0.75	0.56	0.61	0.82	0.70	0.65	0.75	0.55	0.59	0.82	0.69	0.66	0.83	0.71	0.68
P2: FEC>=LRP, rule correct	0.71	0.85	0.83	0.70	0.74	0.78	0.71	0.85	0.83	0.70	0.74	0.78	0.70	0.72	0.75
P1+P2	1.46	1.40	1.43	1.52	1.44	1.43	1.46	1.41	1.43	1.52	1.43	1.44	1.52	1.43	1.43
P3: FEC<LRP, rule incorrect	0.25	0.44	0.39	0.18	0.30	0.35	0.25	0.45	0.41	0.18	0.31	0.34	0.17	0.29	0.32
P4: FEC>=LRP, rule incorrect	0.29	0.15	0.17	0.30	0.26	0.22	0.29	0.15	0.17	0.30	0.26	0.22	0.30	0.28	0.25

	F			G			H			I			J		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.78	0.63	0.50	0.81	0.69	0.60	0.78	0.62	0.48	0.81	0.69	0.60	0.83	0.73	0.65
X	13	8	9	13	13	13	13	8	9	13	13	13	13	13	13
t	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
P1: FEC<LRP, rule correct	0.78	0.59	0.64	0.82	0.73	0.69	0.77	0.59	0.63	0.83	0.73	0.69	0.85	0.74	0.71
P2: FEC>=LRP, rule correct	0.66	0.83	0.81	0.66	0.70	0.75	0.66	0.84	0.82	0.66	0.71	0.75	0.66	0.69	0.72
P1+P2	1.44	1.42	1.45	1.49	1.43	1.43	1.44	1.42	1.45	1.49	1.44	1.44	1.51	1.42	1.43
P3: FEC<LRP, rule incorrect	0.22	0.41	0.36	0.18	0.27	0.31	0.23	0.41	0.37	0.17	0.27	0.31	0.15	0.26	0.29
P4: FEC>=LRP, rule incorrect	0.34	0.17	0.19	0.34	0.30	0.25	0.34	0.16	0.18	0.34	0.29	0.25	0.34	0.31	0.28

	K			L			M			N			O		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.41	0.27	0.17	0.44	0.32	0.23	0.41	0.27	0.17	0.44	0.31	0.23	0.50	0.39	0.32
X	11	7	8	11	7	7	11	7	8	11	7	7	11	7	7
t	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0
P1: FEC<LRP, rule correct	0.80	0.73	0.75	0.82	0.75	0.70	0.80	0.72	0.74	0.82	0.74	0.70	0.82	0.75	0.71
P2: FEC>=LRP, rule correct	0.71	0.85	0.87	0.71	0.84	0.91	0.70	0.84	0.87	0.71	0.84	0.91	0.74	0.82	0.87
P1+P2	1.51	1.57	1.62	1.53	1.59	1.61	1.50	1.57	1.62	1.53	1.58	1.61	1.55	1.57	1.58
P3: FEC<LRP, rule incorrect	0.20	0.27	0.25	0.18	0.25	0.30	0.20	0.28	0.26	0.18	0.26	0.30	0.18	0.25	0.29
P4: FEC>=LRP, rule incorrect	0.29	0.15	0.13	0.29	0.16	0.09	0.30	0.16	0.13	0.29	0.16	0.09	0.26	0.18	0.13

	P			Q			R			S			T		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.68	0.57	0.50	0.74	0.65	0.60	0.68	0.57	0.49	0.74	0.65	0.60	0.77	0.69	0.65
X	11	12	20	11	11	20	11	12	20	11	11	20	11	11	20
t	1	1	4	1	1	4	1	1	4	1	1	4	1	1	4
P1: FEC<LRP, rule correct	0.81	0.73	0.92	0.84	0.71	0.98	0.81	0.71	0.92	0.83	0.70	0.98	0.85	0.71	0.98
P2: FEC>=LRP, rule correct	0.90	0.91	0.74	0.88	0.91	0.69	0.91	0.90	0.75	0.89	0.91	0.69	0.89	0.91	0.65
P1+P2	1.71	1.63	1.66	1.72	1.62	1.66	1.72	1.62	1.67	1.72	1.61	1.67	1.74	1.62	1.63
P3: FEC<LRP, rule incorrect	0.19	0.27	0.08	0.16	0.29	0.02	0.19	0.29	0.08	0.17	0.30	0.02	0.15	0.29	0.02
P4: FEC>=LRP, rule incorrect	0.10	0.09	0.26	0.12	0.09	0.31	0.09	0.10	0.25	0.11	0.09	0.31	0.11	0.09	0.35

Table 4: Summary results for scenarios A-T, for decision rule parameters fixed at *X*=13 and *t*=1.

	A			B			C			D			E		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.82	0.67	0.55	0.86	0.74	0.65	0.82	0.66	0.53	0.85	0.74	0.65	0.87	0.78	0.71
P1: FEC<LRP, rule correct	0.75	0.64	0.58	0.82	0.70	0.65	0.75	0.63	0.57	0.82	0.69	0.66	0.83	0.71	0.68
P2: FEC>=LRP, rule correct	0.71	0.76	0.80	0.70	0.74	0.78	0.71	0.76	0.80	0.70	0.74	0.78	0.70	0.72	0.75
P1+P2	1.46	1.39	1.39	1.52	1.44	1.43	1.46	1.39	1.37	1.52	1.43	1.44	1.52	1.43	1.43
P3: FEC<LRP, rule incorrect	0.25	0.36	0.42	0.18	0.30	0.35	0.25	0.37	0.43	0.18	0.31	0.34	0.17	0.29	0.32
P4: FEC>=LRP, rule incorrect	0.29	0.24	0.20	0.30	0.26	0.22	0.29	0.24	0.20	0.30	0.26	0.22	0.30	0.28	0.25

	F			G			H			I			J		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.78	0.63	0.50	0.81	0.69	0.60	0.78	0.62	0.48	0.81	0.69	0.60	0.83	0.73	0.65
P1: FEC<LRP, rule correct	0.78	0.67	0.63	0.82	0.73	0.69	0.77	0.67	0.61	0.83	0.73	0.69	0.85	0.74	0.71
P2: FEC>=LRP, rule correct	0.66	0.71	0.76	0.66	0.70	0.75	0.66	0.71	0.76	0.66	0.71	0.75	0.66	0.69	0.72
P1+P2	1.44	1.38	1.39	1.49	1.43	1.43	1.44	1.37	1.37	1.49	1.44	1.44	1.51	1.42	1.43
P3: FEC<LRP, rule incorrect	0.22	0.33	0.37	0.18	0.27	0.31	0.23	0.33	0.39	0.17	0.27	0.31	0.15	0.26	0.29
P4: FEC>=LRP, rule incorrect	0.34	0.29	0.24	0.34	0.30	0.25	0.34	0.29	0.24	0.34	0.29	0.25	0.34	0.31	0.28

	K			L			M			N			O		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.41	0.27	0.17	0.44	0.32	0.23	0.41	0.27	0.17	0.44	0.31	0.23	0.50	0.39	0.32
P1: FEC<LRP, rule correct	0.92	0.86	0.83	0.93	0.88	0.85	0.91	0.86	0.83	0.93	0.88	0.85	0.93	0.88	0.86
P2: FEC>=LRP, rule correct	0.48	0.54	0.61	0.49	0.56	0.63	0.47	0.52	0.60	0.48	0.55	0.62	0.51	0.56	0.60
P1+P2	1.40	1.40	1.44	1.42	1.44	1.49	1.38	1.39	1.43	1.41	1.43	1.47	1.44	1.44	1.46
P3: FEC<LRP, rule incorrect	0.08	0.14	0.17	0.07	0.12	0.15	0.09	0.14	0.17	0.07	0.12	0.15	0.07	0.12	0.14
P4: FEC>=LRP, rule incorrect	0.52	0.46	0.39	0.51	0.44	0.37	0.53	0.48	0.40	0.52	0.45	0.38	0.49	0.44	0.40

	P			Q			R			S			T		
LRP	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15	10	12.5	15
Proportion above LRP	0.68	0.57	0.50	0.74	0.65	0.60	0.68	0.57	0.49	0.74	0.65	0.60	0.77	0.69	0.65
P1: FEC<LRP, rule correct	0.90	0.81	0.77	0.91	0.83	0.82	0.90	0.80	0.76	0.91	0.82	0.81	0.90	0.82	0.79
P2: FEC>=LRP, rule correct	0.76	0.82	0.88	0.74	0.78	0.83	0.76	0.82	0.87	0.74	0.78	0.82	0.73	0.76	0.79
P1+P2	1.65	1.62	1.65	1.65	1.62	1.64	1.66	1.62	1.63	1.65	1.61	1.63	1.64	1.59	1.59
P3: FEC<LRP, rule incorrect	0.10	0.19	0.23	0.09	0.17	0.18	0.10	0.20	0.24	0.09	0.18	0.19	0.10	0.18	0.21
P4: FEC>=LRP, rule incorrect	0.24	0.18	0.12	0.26	0.22	0.17	0.24	0.18	0.13	0.26	0.22	0.18	0.27	0.24	0.21

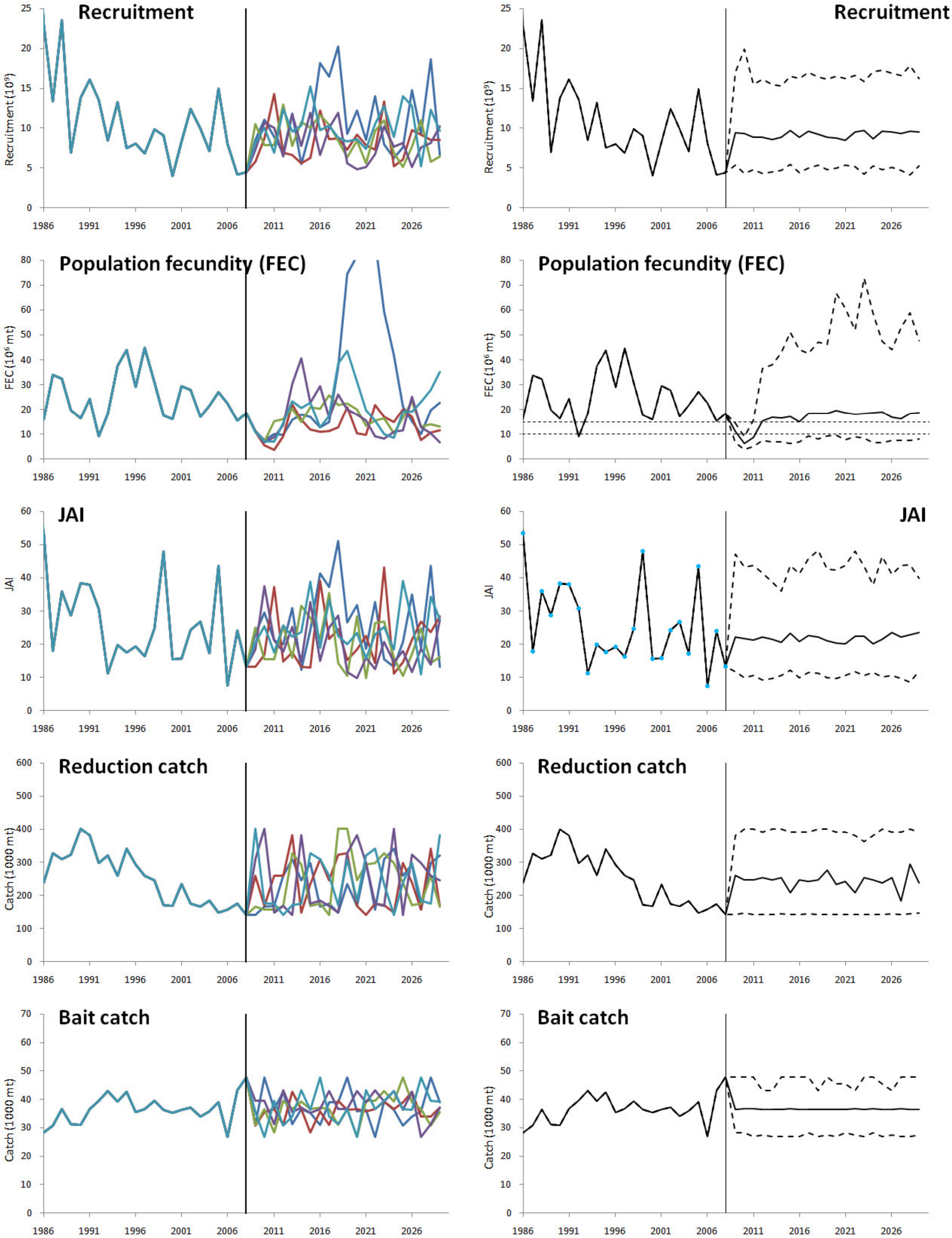

Fig. 1: Worm plots (five trajectories) (left column) and medians (full line) and 95% probability envelopes (dashed lines) (right column) for a series of statistics for scenario A. The horizontal dashed lines for *FEC* indicate the range of values considered for a LRP.

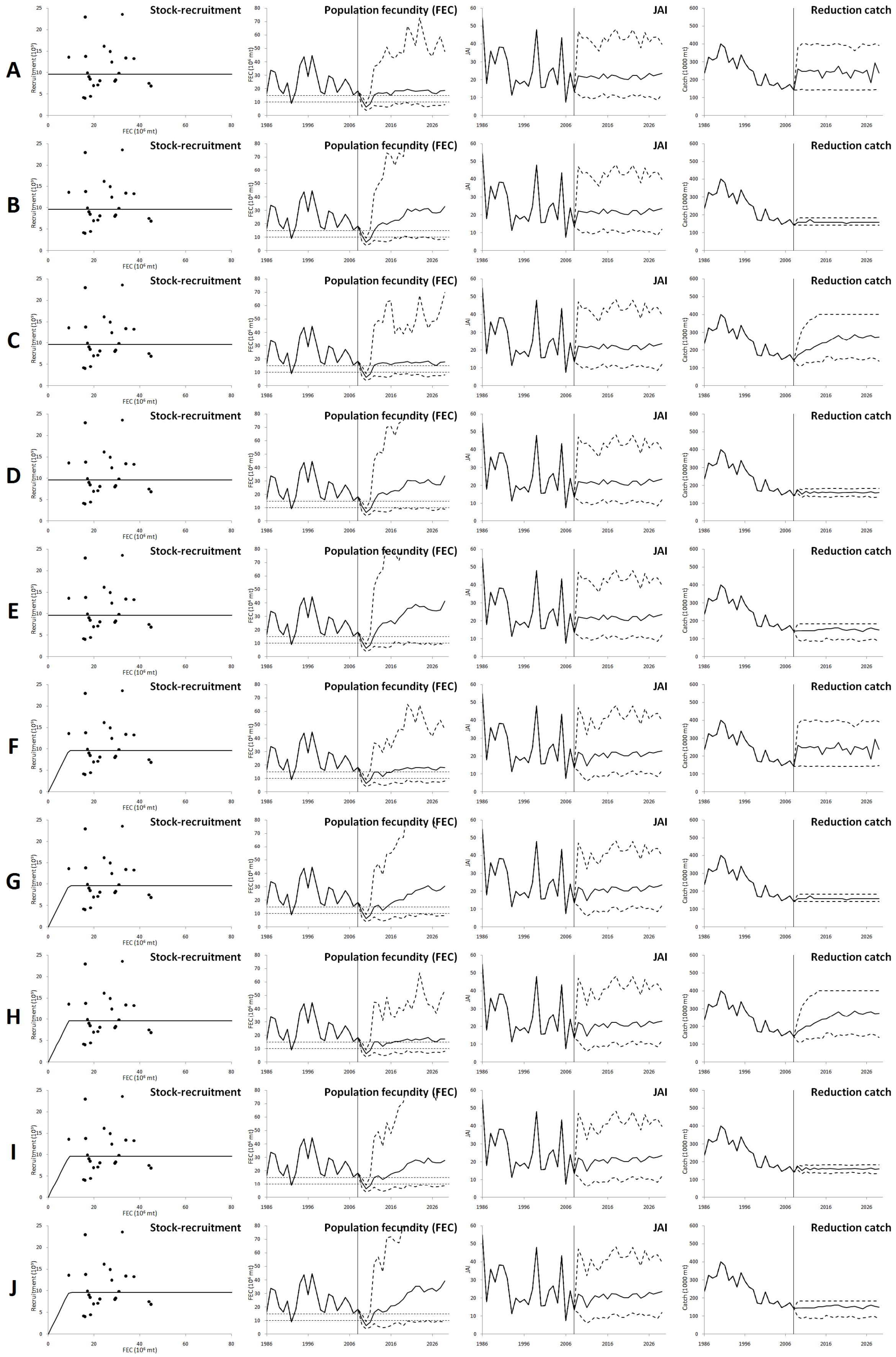

Fig. 2a: Medians (full line) and 95% probability envelopes (dashed lines) for a series of trajectories for scenarios A-J. The horizontal dashed lines for *FEC* indicate the range of values considered for a LRP.

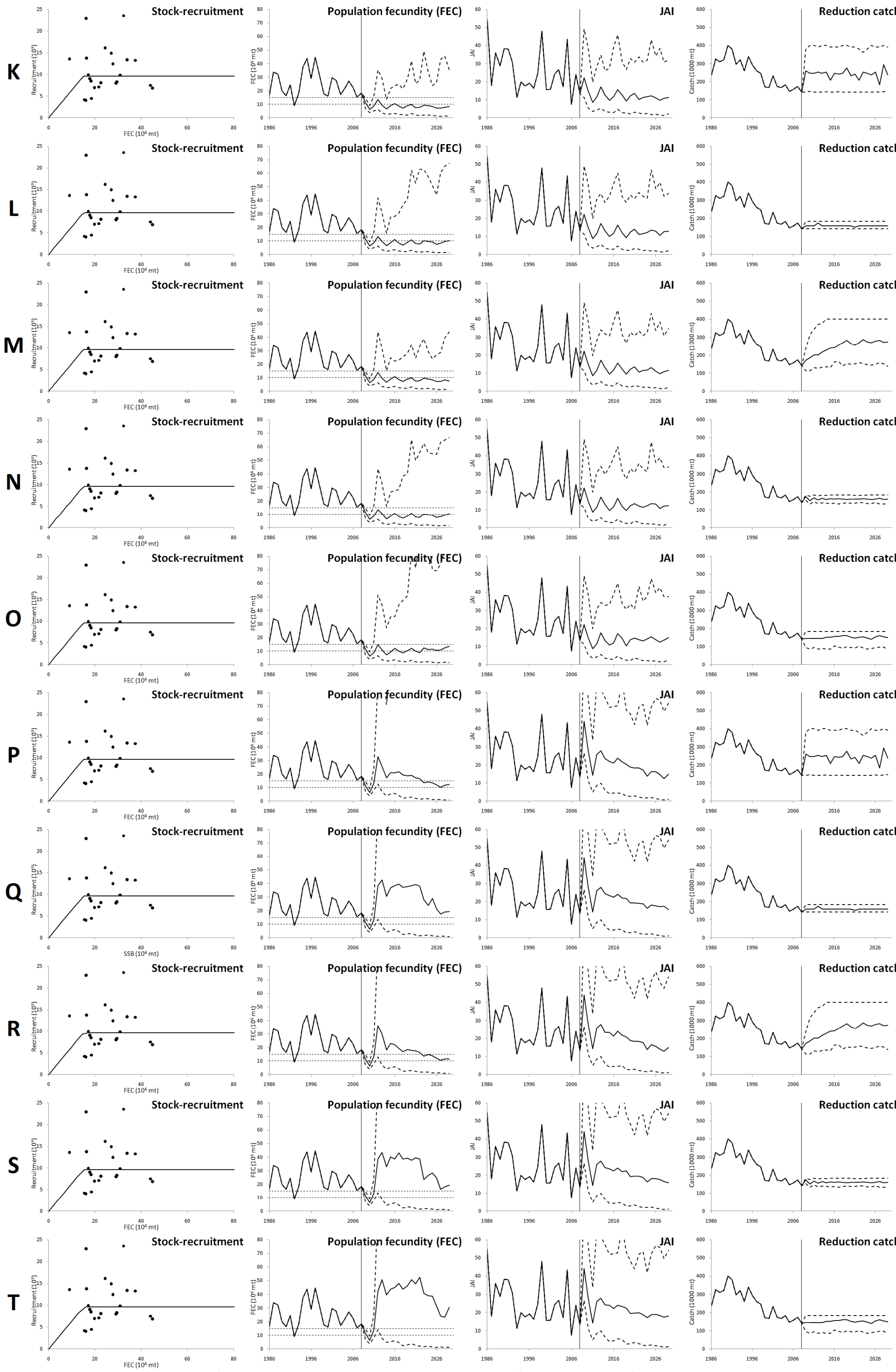

Fig. 2b: Medians (full line) and 95% probability envelopes (dashed lines) for a series of trajectories for scenarios K-T. The horizontal dashed lines for *FEC* indicate the range of values considered for a LRP.

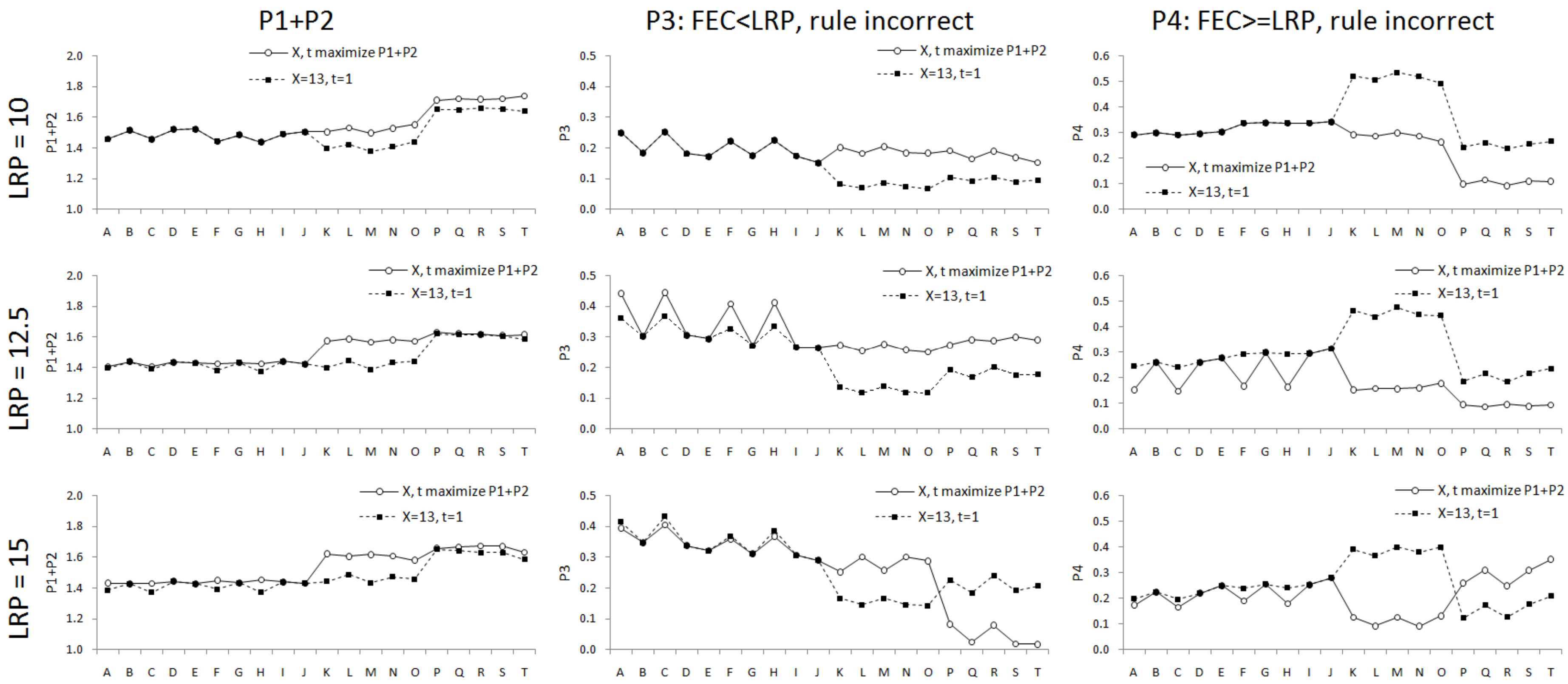

Fig. 3: Summary results for scenarios A-T, where decision rule parameters *X* and *t* are chosen to maximize P1+P2 (full line, open circles) and where these parameters are fixed at *X*=13 and *t*=1 (dashed line, black squares).

APPENDIX : Projection Methodology for Atlantic Menhaden

Projection methodology

Projections into the future are carried out using the following steps. The data used are listed in Tables A1 to A8 – note that where necessary these have been revised from the results given in ASMFC (2010) to incorporate corrections for some errors recently discovered in the BAM assessment reported there (Amy Schueller, pers. commn).

Step 1: Begin-year numbers at age

The begin-year numbers-at-age vector (for 2008) is obtained from the base BAM assessment of the resource (ASMFC. 2010) for year 1955-2008 (Table A1).

Step 2: Catch

These numbers-at-age at the start of year *y* ($N_{y,a}$ where *a* refers to age in years) are projected one year forward at a time given a catch and fishing selectivity for the year concerned.

For 2008:

A reduction catch (C_{2008}^{red}) of 141 100t and a bait catch (C_{2008}^{bait}) of 47 738t are assumed with the selectivities as estimated in the base BAM assessment (Table A3).

From 2009 onwards:

C_y^{bait} and $S_{y,a}^{bait}$ (the selectivity-at-age for the bait fishery) are sampled randomly with replacement from C_y^{bait} and $S_{y,a}^{bait}$ for the period 1986-2008 (the same random year is used for the catch and the selectivity) (Tables A2 and A3a).

For C_y^{red} , a number of options are tested:

a) C_y^{red} and $S_{y,a}^{red}$ are sampled randomly with replacement from C_y^{red} and $S_{y,a}^{red}$ for the period 1986-2008 (the same randomly selected year is used for both the catch and the selectivity) (Tables A2 and A3b).

b) C_y^{red} and $S_{y,a}^{red}$ are sampled randomly from C_y^{red} and $S_{y,a}^{red}$ for the period 2004-2008 (the same randomly selected year is used for both the catch and the selectivity).

c) First order autocorrelation in the catches is assumed:

$$C_{y+1}^{red} = \overline{C}\exp\left[b\left(C_y^{red} - \overline{C}\right)/\overline{C} + \varepsilon_y\right] \quad \text{(A1)}$$

where $$\overline{C} = \sum_{y=y1}^{2008} C_y^{red} \Big/ \sum_{y=y1}^{2008} 1 \quad \text{(A2)}$$

$\varepsilon_y \approx N\left(0, \sigma_C^2\right)$,and

subject to the constraint $C_y^{red} \leq= \max\left[C_y^{red}(1986-2008)\right]$.

b is estimated by minimising the following negative log-likelihood:

$$-\ln L^C = \sum_{y=y1+1}^{2008}\left[\ln\sigma_C + \frac{\varepsilon_y^2}{2\sigma_C^2}\right] \quad \text{(A3)}$$

with

$$\sigma_C^2 = \sum_{y=y1+1}^{2008}\varepsilon_y^2 \Big/ \sum_{y=y1+1}^{2008} 1 \quad \text{(A4)}$$

Two periods are considered, commencing at y_1=1986 and at y_1=2004. The selectivity is selected at random with replacement from $S_{y,a}^{red}$ for the period y_1-2008.

The values estimated for *b* and σ_C are:

for y_1=1986: $\sigma_C = 0.20$ and *b*=0.86;

for y_1=2004: $\sigma_C = 0.06$ and *b*=-0.68;

Step 3: Catch-at-age

Given the reduction and bait catches C_y^{red} and C_y^{bait} specified as above, then:

$$F_y^f = C_y^f \Big/ \sum_a w_{y,a}^{mid} N_{y,a}\, e^{-M_{y,a}/2} S_{y,a}^f \quad \text{(A5)}$$

for each fleet *f* (where *f* = *red* or *bait*), where $w_{y,a}^{mid}$ and $M_{y,a}$ are each year selected randomly from the weight-at-age vectors (Table A4) and the natural mortality-at-age vectors (Table A5) for the 1986-2008 period used in the assessment, and hence:

$$C_{y,a}^f = N_{y,a}\, e^{-M_{y,a}/2} S_{y,a}^f F_y^f \quad \text{(A6)}$$

The future numbers-at-age can then be computed for the beginning of the following year (*y*+1):

$$N_{y+1,0} = R_{y+1} \quad \text{(A7)}$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_{y,a}/2} - \sum_f C_{y,a}^f\right) e^{-M_{y,a}/2} \qquad \text{for } 0 \le a \le m-1 \quad \text{(A8)}$$

$$N_{y+1,m} = \left(N_{y,m-1}\, e^{-M_{y,m-1}/2} - \sum_f C_{y,m-1}^f\right) e^{-M_{y,m-1}/2} + \left(N_{y,m}\, e^{-M_{y,m}/2} - \sum_f C_{y,m}^f\right) e^{-M_{y,m}/2} \quad \text{(A9)}$$

These equations reflect Pope's approximation.

The maximum age *m* is taken to be 8 (a plus-group).

Step 4: Recruitment

Future recruitments (age 0) are provided by a (geometric) average recruitment over a previous period or by a hockey-stick stock-recruitment relationship, with or without autocorrelation in the residuals about this relationship:

Average recruitment:

$$R_y = \alpha e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} \tag{A10}$$

Hockey-stick:

$$R_y = \begin{cases} \alpha e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } FEC_y \geq FEC_{hinge} \\ \dfrac{\alpha}{FEC_{hinge}} FEC_y e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } FEC_y < FEC_{hinge} \end{cases} \tag{A11}$$

where

$$\varepsilon_y^{SR} = \rho \varepsilon_{y-1}^{SR} + \sqrt{1-\rho^2}\,\zeta_y$$

with ζ_y from $N(0, \sigma_R^2)$,

$$\alpha = \exp\left(\sum_{y=1986}^{2008} \ln R_y \Big/ 23 \right) \tag{A12}$$

Two hockey-stick stock-recruitment relationships are tested:

a) $FEC_{hinge} = \min(FEC_y)$ for the 1986-2008 period = 8.99 million mt, and

b) $FEC_{hinge} =$ 15 million mt, corresponding roughly to a cluster of *FEC* values immediately above the minimum.

When autocorrelation in the stock-recruitment residuals is assumed, ρ is estimated by minimising the following negative log-likelihood function, otherwise $\rho = 0$:

$$-\ln L^{SR} = \sum_{2000}^{2009} \left[\ln \sigma_R + \left(\frac{\varepsilon_y^{SR} - \rho \varepsilon_{y-1}^{SR}}{\sqrt{1-\rho^2}} \right)^2 \Big/ 2\sigma_R^2 \right] \tag{A13}$$

with

$$\sigma_R = \sqrt{1/23 \sum_{y=1986}^{2008} \left(\varepsilon_y^{SR}\right)^2} \tag{A14}$$

$$FEC_y = \sum_{a=1}^{m} 0.5 m_a f_{y,a} N_{y,a} \tag{A15}$$

where $f_{y,a}$ is each year selected randomly from the fecundity-at-age vectors for 1986 to 2008 period used in the assessment (Table A6), and

m_a is the maturity-at-age (Table A7).

Step5:

The information obtained in Step 1 is used to generate a value of the JAI recruitment index JAI_{2009}. Indices of recruitment in this and further future years will not be exactly proportional to true recruitment, as they are subject to observation error. Log-normally distributed observation error is therefore added to the expected value of the recruitment index evaluated:

$$JAI_y = qR_y e^{\varepsilon_y} \tag{A16}$$

$$\varepsilon_y \quad \text{from } N\left(0, \sigma^2\right) \tag{A17}$$

The constant of proportionality q is as estimated by:

$$\ell n\, \hat{q} = 1/23 \sum_{y=1986}^{2008} \left(\ln JAI_y - \ln R_y\right) \tag{A18}$$

and σ by:

$$\sigma^2 = \frac{1}{23} \sum_{1986}^{2008} \left(\ln JAI_y - qR_y\right)^2 \tag{A19}$$

Step 6:

Steps 1-5 are repeated for each future year in turn for as long a period as desired. Each rule under review is assessed by considering statistics such as the probability that the rule is correct when *FEC* is below or is above the Limit Reference Point (LRP) value specified. The rules investigated take the following form:

$$\sum_{y-3-t}^{y-3} JAI_y \Big/ (t+1) \leq X \tag{A20}$$

The form of this rule is motivated by an age at maturity of about 3, so that *FEC* will depend on values of recruitment from three (and more) years earlier.

This has been investigated for a series of LRPs and *X* values.

Table A1: Estimated numbers-at-age (in billions) for Atlantic menhaden at the start of the fishing year from the base BAM model for the period 1986-2008 (Amy Schueller, pers. commn).

	0	1	2	3	4	5	6	7	8
1986	22.971	10.628	3.734	0.226	4.43E-03	6.79E-04	3.87E-05	5.24E-06	2.26E-07
1987	13.384	6.329	3.151	0.790	2.96E-02	6.12E-04	9.39E-05	5.27E-06	7.44E-07
1988	23.566	4.327	2.177	0.668	9.92E-02	3.68E-03	7.67E-05	1.17E-05	7.49E-07
1989	6.943	8.168	1.430	0.384	5.43E-02	7.52E-03	2.82E-04	5.90E-06	9.59E-07
1990	13.776	2.627	2.931	0.170	1.37E-02	1.68E-03	2.34E-04	8.84E-06	2.15E-07
1991	16.111	5.068	1.026	0.461	9.60E-03	6.82E-04	8.38E-05	1.18E-05	4.56E-07
1992	13.553	6.053	1.609	0.072	5.76E-03	9.38E-05	6.59E-06	8.17E-07	1.19E-07
1993	8.455	5.393	2.449	0.193	1.81E-03	1.16E-04	1.91E-06	1.34E-07	1.90E-08
1994	13.242	3.113	2.096	0.565	1.90E-02	1.62E-04	1.05E-05	1.78E-07	1.43E-08
1995	7.498	4.861	1.289	0.625	1.04E-01	3.29E-03	2.84E-05	1.90E-06	3.48E-08
1996	8.007	2.487	1.932	0.272	5.97E-02	8.89E-03	2.85E-04	2.52E-06	1.71E-07
1997	6.848	2.806	1.020	0.559	4.40E-02	8.92E-03	1.33E-03	4.33E-05	4.10E-07
1998	9.849	2.342	1.130	0.291	9.15E-02	6.67E-03	1.35E-03	2.02E-04	6.64E-06
1999	9.060	3.171	0.845	0.229	2.44E-02	6.86E-03	4.94E-04	9.93E-05	1.54E-05
2000	4.028	2.904	1.272	0.176	1.83E-02	1.72E-03	4.88E-04	3.46E-05	8.03E-06
2001	8.290	1.333	1.257	0.368	2.52E-02	2.39E-03	2.26E-04	6.46E-05	5.63E-06
2002	12.420	2.628	0.534	0.316	4.59E-02	2.88E-03	2.73E-04	2.62E-05	8.11E-06
2003	9.928	3.912	0.992	0.127	3.48E-02	4.51E-03	2.88E-04	2.75E-05	3.45E-06
2004	7.094	3.225	1.507	0.255	1.60E-02	4.05E-03	5.28E-04	3.44E-05	3.70E-06
2005	14.922	2.031	1.186	0.389	3.62E-02	2.09E-03	5.50E-04	7.33E-05	5.29E-06
2006	8.083	4.459	0.680	0.328	5.96E-02	5.22E-03	3.08E-04	8.44E-05	1.21E-05
2007	4.157	2.376	1.490	0.146	3.52E-02	5.87E-03	5.30E-04	3.24E-05	1.01E-05
2008	4.447	1.301	0.847	0.289	1.12E-02	2.42E-03	4.15E-04	3.87E-05	3.11E-06

Table A2: Reduction and bait landings for Atlantic menhaden for the period 1986-2008 (ASMFC, 2010, Appendix A.3).

	Reduction landings (1000 mt)	Bait landings (1000 mt) (includes MRFSS landings)
1986	238.0	28.3
1987	327.0	30.9
1988	309.3	36.6
1989	322.0	31.2
1990	401.2	31.0
1991	381.4	36.6
1992	297.6	39.6
1993	320.6	43.0
1994	260.0	39.3
1995	339.9	42.6
1996	292.9	35.4
1997	259.1	36.6
1998	245.9	39.4
1999	171.2	36.4
2000	167.2	35.4
2001	233.7	36.4
2002	174.0	37.2
2003	166.1	34.1
2004	183.4	35.8
2005	146.9	39.0
2006	157.4	26.9
2007	174.5	43.1
2008	141.1	47.7

Table A3a: Estimated selectivity-at-age for the bait fishery from the base BAM assessment (Amy Schueller, pers. commn).

	0	1	2	3	4	5	6	7	8
1986	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1987	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1988	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1989	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1990	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1991	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1992	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1993	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1994	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1995	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1996	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1997	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1998	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
1999	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2000	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2001	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2002	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2003	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2004	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2005	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2006	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2007	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000
2008	0.000	0.007	0.208	0.901	0.997	1.000	1.000	1.000	1.000

Table A3b: Estimated selectivity-at-age for the reduction fishery from the base BAM assessment (Amy Schueller, pers. commn).

	0	1	2	3	4	5	6	7	8
1986	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1987	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1988	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1989	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1990	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1991	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1992	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1993	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1994	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1995	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1996	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1997	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1998	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
1999	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2000	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2001	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2002	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2003	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2004	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2005	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2006	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2007	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000
2008	0.009	0.096	0.554	0.935	0.994	0.999	1.000	1.000	1.000

Table A4: Atlantic menhaden weight-at-age (g) in the fishery (ASMFC 2010, Appendix A.3).

	0	1	2	3	4	5	6	7	8
1986	24.3	64.4	149.8	230.7	375.2	470.7	516.2	715.8	683.0
1987	26.6	75.5	153.6	249.4	338.2	476.8	533.3	566.0	847.6
1988	27.8	69.4	159.9	241.3	329.2	429.6	541.5	556.9	580.4
1989	39.1	91.1	150.3	256.1	341.1	427.5	567.7	657.1	632.2
1990	35.8	113.1	208.5	248.2	340.4	419.4	494.0	670.6	713.7
1991	52.0	92.8	224.1	309.7	334.8	393.4	461.9	521.5	723.5
1992	28.3	123.1	186.4	318.7	392.3	420.5	445.0	512.0	565.8
1993	49.8	93.4	243.6	294.7	396.0	457.6	501.1	488.5	553.9
1994	23.5	118.8	214.3	355.7	395.0	450.3	504.8	572.6	523.3
1995	22.6	112.6	229.7	331.8	423.1	453.4	456.3	501.1	586.3
1996	17.0	96.5	288.8	371.6	483.5	529.8	564.3	517.7	564.7
1997	28.8	87.6	246.6	447.0	491.0	594.2	585.9	625.8	536.0
1998	60.3	93.9	227.2	390.9	547.0	574.4	662.1	608.2	654.1
1999	39.1	131.1	214.0	354.9	496.6	597.8	627.1	699.9	612.1
2000	27.1	131.5	252.7	345.5	456.5	577.9	633.4	674.5	736.3
2001	55.0	125.1	280.6	382.9	462.1	522.0	624.5	643.7	697.6
2002	40.4	149.4	290.1	422.1	526.3	581.0	588.9	683.6	677.6
2003	49.5	121.7	277.0	440.1	557.5	701.6	725.3	678.0	779.9
2004	27.0	113.9	238.6	339.2	482.6	572.9	738.6	722.8	638.4
2005	37.3	81.3	214.5	328.6	369.5	495.8	572.7	760.5	714.6
2006	45.3	111.1	185.4	321.5	411.2	407.1	537.6	619.3	862.4
2007	50.2	119.8	219.0	297.3	390.9	434.4	399.2	514.3	588.0
2008	52.4	123.8	247.9	313.7	424.9	473.5	479.2	419.4	539.6

Table A5: Natural mortality-at-age for Atlantic menhaden used in the base BAM assessment (ASMFC, 2010, Appendix A.3).

	0	1	2	3	4	5	6	7	8
1986	1.279	1.106	0.863	0.675	0.525	0.516	0.532	0.532	0.532
1987	1.117	0.936	0.757	0.602	0.511	0.495	0.499	0.499	0.499
1988	1.044	0.940	0.711	0.581	0.516	0.493	0.489	0.489	0.489
1989	0.950	0.789	0.678	0.565	0.510	0.490	0.482	0.482	0.482
1990	0.981	0.736	0.603	0.537	0.500	0.486	0.476	0.476	0.476
1991	0.948	0.814	0.609	0.526	0.501	0.491	0.481	0.481	0.481
1992	0.900	0.670	0.588	0.503	0.481	0.451	0.452	0.452	0.452
1993	0.986	0.802	0.562	0.519	0.485	0.458	0.429	0.429	0.429
1994	0.993	0.783	0.596	0.504	0.483	0.460	0.432	0.432	0.432
1995	1.089	0.764	0.584	0.514	0.497	0.473	0.448	0.448	0.448
1996	1.038	0.778	0.540	0.482	0.467	0.459	0.442	0.442	0.442
1997	1.062	0.793	0.541	0.470	0.453	0.450	0.443	0.443	0.443
1998	1.118	0.853	0.564	0.478	0.445	0.448	0.450	0.450	0.450
1999	1.124	0.763	0.588	0.496	0.466	0.448	0.464	0.464	0.464
2000	1.096	0.732	0.548	0.495	0.475	0.461	0.454	0.454	0.454
2001	1.137	0.785	0.570	0.510	0.483	0.474	0.465	0.465	0.465
2002	1.143	0.842	0.591	0.516	0.504	0.479	0.471	0.471	0.471
2003	1.114	0.841	0.618	0.533	0.492	0.479	0.458	0.458	0.458
2004	1.241	0.895	0.673	0.557	0.535	0.487	0.465	0.465	0.465
2005	1.199	0.997	0.653	0.565	0.526	0.496	0.458	0.458	0.458
2006	1.212	0.962	0.696	0.572	0.538	0.500	0.463	0.463	0.463
2007	1.149	0.895	0.723	0.585	0.536	0.497	0.464	0.464	0.464
2008	1.130	0.863	0.639	0.605	0.550	0.498	0.463	0.463	0.463

Table A6: Fecundity-at-age (g) for Atlantic menhaden used in the base BAM assessment (ASMFC, 2010, Appendix A.3).

	0	1	2	3	4	5	6	7	8
1986	11194	17507	40211	66869	124164	179809	209812	314420	317127
1987	11694	19044	39900	72507	107028	178377	223223	247684	430450
1988	10781	18729	43140	72525	112059	159064	235350	259482	279125
1989	14167	21067	40486	76556	111879	154549	222090	290944	288137
1990	14328	26370	54852	72906	114475	153221	195960	294199	342191
1991	17301	23607	63019	100508	114209	151802	192481	233508	372828
1992	11794	30181	52052	107864	147453	160861	185035	227120	265781
1993	17271	21825	68848	92673	150265	187929	208910	212599	256089
1994	9100	29252	56433	119239	141157	184363	219109	255020	234350
1995	9443	22337	66500	110187	171898	191874	209152	241463	296939
1996	8052	20339	74449	119511	176526	219312	240032	226078	256774
1997	11702	18123	61582	149569	181602	246020	257940	282628	237196
1998	20099	21649	56881	125462	224089	244805	310820	287369	318397
1999	12914	32600	56379	115806	198170	283248	302967	366460	308808
2000	9448	27803	71927	111449	180157	265805	324435	352755	411527
2001	16749	24031	79355	131544	181048	237106	320982	350990	393221
2002	12987	32813	77921	148231	208483	255753	281249	362328	367363
2003	16723	25692	76840	145560	215084	296236	327068	312738	391655
2004	11381	27874	65996	121075	202863	268489	387280	389664	334063
2005	12405	19744	61521	116790	154373	241983	306415	475127	441406
2006	15423	24841	48597	107766	164962	175774	265745	331510	555314
2007	2563	27610	63581	96542	160275	203292	188400	279302	347428
2008	2563	2563	68958	110408	162892	212289	230685	195515	286783

Table A7: Female maturity-at-age for Atlantic menhaden used in the base BAM assessment (ASMFC, 2010, Appendix A.3).

0	1	2	3	4	5	6	7	8
0.00	0.00	0.13	0.85	1.00	1.00	1.00	1.00	1.00

Table A8: Estimated past population fecundity (*FEC*) (as calculated for the analyses of this paper) and past JAI values used for the base BAM assessment (ASMFC 2010, Appendix A.3).

	FEC (10^6 mt)	JAI
1986	16.14	53.46
1987	33.89	17.93
1988	32.33	35.90
1989	19.79	28.73
1990	16.25	38.38
1991	24.38	38.01
1992	8.99	30.79
1993	18.29	11.22
1994	37.42	19.85
1995	43.91	17.51
1996	29.09	19.27
1997	44.78	16.33
1998	30.87	24.70
1999	17.73	47.97
2000	16.04	15.52
2001	29.46	15.75
2002	27.73	24.23
2003	17.12	26.76
2004	21.66	17.20
2005	27.01	43.51
2006	22.55	7.40
2007	15.38	24.02
2008	18.45	13.20