APPENDIX 5. Stochastic Projections in the Context of the Precautionary Approach

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Appendix 5: Stochastic Projections in the Context of the Precautionary Approach

by

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Abstract

This document is intended as a tutorial to explore risk analyses using spreadsheets. The tutorial uses @Risk, an Add-in to the Excel spreadsheet software to add risk analysis capabilities to your models. The Add-in provides a framework to handle probability distributions for any variable or input parameter to a model. It also provides tools to analyze the distribution of the results, i.e. any calculated field (or cell) dependent upon your input. The concepts are applied to a fisheries model allowing long-term projections in the context of the Precautionary Approach.

Introduction

This document is intended as a tutorial for the use of @Risk (Anon. 2000), an Add-in to Excel (Microsoft Corp., WA, USA), in the context of fishery models. This add-in allows a user to specify probability distributions for any variable or parameter of a model specified in an Excel spreadsheet. It also provides the tools necessary to analyze the distribution of the results, i.e. of any calculated field (or cell) dependent upon input quantity (or cell).

In this tutorial, we will 1) learn how to use @risk functions, 2) explore @Risk menus for setting up a simulation, 3) develop a simple model and run a simulation, 4) explore results using @Risk interface, 5) apply what we have learned to a model allowing long term projections in the context of Precautionary Approach (PA) frameworks.

Simple Model for Tutorial

A simple model will first be constructed to explore the use of @Risk functions for simulating probability distributions. Load the spreadsheet "LogNormal Study.xls". Type the following equations in the designated cells:

Cell	Equation
B9	=RiskNormal(B5,C5)
C9	=RiskStdDev(B9)
D9	=RiskOutput() + EXP(B9)
E9	=RiskStdDev(D9)
F9	=RiskMean(D9)
G9	=RiskPercentile(D9, 0.5)
H9	=RiskMean(B9)

You have entered three types of @Risk functions. The first type, such as RiskNormal(mean, standard deviation) describes a probability distribution of an input to your model (parameter or variable). The second type, such as RiskStdDev(B9), allows you to monitor the characteristics of a distribution for a cell (here Excel cell B9). The third type, such as RiskOutput(), tells @Risk that this is an entry that you want to monitor with @Risk; @Risk will monitor the distribution of the values of this output cell when the input cells are sampled during simulations.

At this point, load @Risk. The @Risk software is generally loaded from the Windows Start Menu, under "Programs - Palisade Decision Tools / @Risk 4.0 for Excel".

1. In Excel sheet "LogNormal Study.xls":
2. Select the "Simulation Settings" Menu.
3. Select "Iterations" tab.
4. Enter 1000 in the "# iterations" box.
5. Ensure that the "Update display" selection is marked.
6. Select the "Sampling" tab.
7. Ensure that the "Latin Hypercube" selection is marked.
8. Click OK.
9. Select the "Start Simulation" Menu. The simulation will start. When the simulation is completed, the Risk Result display will appear. The "Summary Statistics" sheet in Tab 1 summarizes the statistics (minimum, mean, maximum, etc.) for each of the output and input cells.
10. In the @Risk Explorer window, select the Output marked "D9-Normal(lnN,lnSD / N" entry.
11. Select "Insert / Detailed Statistics". The detailed statistics sheet will appear.
12. Because we have used the @Risk functions to return the results to our spreadsheet, the results of interest also appear in the proper cells in the Excel spreadsheet. Return to the Excel sheet by selecting the Excel Icon. See the results displayed in F9 and G9: these cells provide the mean and median of D9, respectively. While the @Risk Output functions are useful to return results quickly to your spreadsheet, you can always go back to the @Risk menus to get more details on the statistics of your input or results.

As an exercise, we will now use the log-normal functions of @Risk to generate log-normal data directly. @Risk provides two ways to generate log-normal data. We will use the LogNormal2 function to generate log-normal data directly from the parent normal distribution.

Type the following equations in the designated cells:

Cell	Equation
D10	=RiskLogNorm2(B5,C5)
B10	=RiskOutput() + LN(D10)
C10	=RiskStdDev(B10)

Note that you can display the distribution of an input cell by selecting the Define distribution icon on the @Risk Toolbar.

Select cells E9-H9 and paste starting at the E10 cell. The following entries will be created.

Cell	Equation
E10	=RiskStdDev(D10)
F10	=RiskMean(D10)
G10	=RiskPercentile(D10, 0.5)
H10	=RiskMean(B10)

Repeat steps 9–12 above to run a new simulation. You should **note that the value displayed in an Excel cell does not necessarily correspond to the mean of the inherent distribution**. Inspect the results of D9 and F9, for example. What is displayed in D9 is EXP(value displayed in B9), not the mean of the distribution in D9. If a cell contains an @Risk distribution, @Risk provides options to display in this cell either the last value sampled or the expected value of the underlying distribution. When working with distributions and @Risk functions, it is important to make a distinction between what is displayed at the end of a simulation and the characteristics (mean, median, etc.) of the distribution underlying a given cell/entry.

@Risk Functions

There are more than 30 distribution functions available in @Risk. You can invoke the functions like you would do for any Excel-function, either by typing them directly into any cell, or by using the menu.

13. In Excel sheet "LogNormal Study.xls":
14. Select the cell D12.
15. Select the "Insert/Function" Menu.
16. In the "Function Category:" box, select @Risk Distribution.
17. In the "Function Category:" box, scan the list to get an appreciation of the distributions available. Select RiskLogNormal.
18. You will see a menu allowing you to specify the Mean and Standard deviation for the function. Enter D6 for the Mean and E5 for the standard deviation. Click OK.
19. The function will be inserted in cell D12.

Graphical Output of Results in Spreadsheet

You can produce a graph of the distribution of any "input" or "output" cell directly in the Excel spreadsheet by using the RiskResultsGraph() function.

Cell	Equation
A15	=RiskResultsGraph(D9,B15:F30,0,TRUE,5,95)
A32	=RiskResultsGraph(D10,B32:F47,0,TRUE,5,95)
A49	=RiskResultsGraph(D12,B49:F64,0,TRUE,5,95)

Repeat steps 9–12 above to generate the Graph.

Discussion:

This part of the tutorial was intended to set up the stage for a discussion on the input to be used in long-term projections. What should be the distribution of the abundance estimates for the starting year, for instance? Note how different the distributions could be, depending on what distribution is used to generate the input.

For estimates coming from an ADAPT model (see Rivard and Gavaris, 2000), the common practice has been to use the log-normal distribution with a mean corresponding to the bias-corrected estimate on the arithmetic scale and with a standard deviation corresponding to the standard error of the estimate. Bias-correction is suggested because ADAPT uses a non-linear estimation procedure to get its estimates. Simulations attempting to simulate the assessment procedure suggest that the bias-corrected results give estimates that are consistent with the "true" value. Note that this aspect is still under active investigation by a number of experts.

The point here is that for your projections to be representative of the real world, care should be taken to model distributions that are consistent with your observations and with the dynamics of your stock (e.g. no negative values possible, etc.). Insights on the error structure of the inputs for @Risk models require thorough investigation of available data.

You can also generate graphs from the @Risk – Results sheet.

20. In the @Risk Explorer window, select the Output marked "D9-Normal(lnN,lnSD / N" entry.
21. Select "Insert / Graph / Histogram". The histogram will appear in a separate sheet. You can change the format of this graph by using one of the "Format Active Graph" Icons.

Adding and Removing the Output Function from Selected Cells

To monitor the distribution of a given variable (or cell), you need to add the Output function to that cell. You can do this by entering the RiskOutput() function directly in the cell, as was done in cell B10 above, or by clicking the "Add to Output" Icon in the @Risk menu. For example, cell B12 has been defined as follows:

Cell	Equation
B12	=LN(D12)

22. In Excel sheet "LogNormal Study.xls":
23. Select the cell B12.
24. Select the "Add Output" icon. That cell will be added to the output list. You will see that the function RiskOutput() has been added to the B12 cell, i.e. added to its original content.
25. You can also check that B12 is indeed in the Ouput list by selecting the "Display List of Outputs and Inputs" icon. Do it now. The @Risk-Model panel will appear.

To remove a variable or cell from the Output list, do the following:

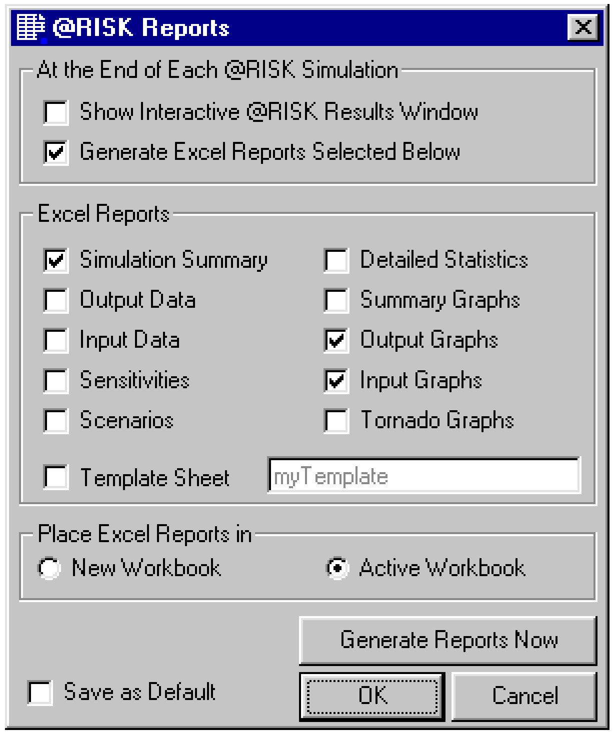
26. In Excel sheet "LogNormal Study.xls":
27. Select the "Display List of Outputs and Inputs" icon.
28. Select the cells for which you wish to delete from the Output list in the @Risk explorer's window.
29. Select from the menu "Model / Delete Ouputs". You will be asked "Are you sure you want to delete this ouptut?". Select Yes. The RiskOutput() function will be deleted from the cells selected. Note that the original formula in this cell remains intact. Only the RiskOuput() function has been removed, so that the cell will not be monitored anymore by @Risk.

Reports

Simulations results may be displayed in the @Risk Results Window or sent directly to the Excel spreadsheet.

30. In Excel sheet "LogNormal Study.xls":
31. Select the "Report Settings" icon on the @Risk tooolbar.
32. In the "At the End of Each @Risk Simulation" section, select only "Generate Excel Reports Selected Below".
33. In the "Excel Reports" section: Select "Simulation Summary", "Ouput Graphs" and "Input Graphs".
34. In the "Place Excel reports in" section: select "Active Workbook".
35. Select the OK button to activate these options.

At the end of step 34, the @Risk Report template should look like this:



Run a simulation now to see how these reports are generated. The reports selected will be put automatically your excel spreadsheet at the end of each simulation. Note that if you have many Input and Output cells in your model, the number of graphs could be large. In such a case, you should probably focus on key cells and generate the graphs of interests directly in Excel using the procedures explained in the "Graphical Output of Results in Spreadsheet" section (see above).

Identification of Entries in @Risk Interactive Windows

Go to the @Risk-Results Window to see how @Risk identifies Input and Output cells in its interactive windows. For instance, one of the inputs is identified as "D9 – Normal(lnN, lnSD / N". The cell for this input is D9. @Risk also adds labels by scanning your spreadsheet for the nearest label to the left of the cell of interest, as well as the nearest label above the cell of interest. In the case at hand, the nearest label to the left is "Normal(lnN, lnSD)" and the nearest label above D9 is "N".

Entering descriptive labels in strategic locations makes it easier to analyze your results in the @Risk Interactive Windows. Note that values corresponding to "years" and "ages" generated through Excel formulas are not "seen" as labels. You must create labels from these formulas (i.e. where numbers are defined as "text") to allow @Risk to generate proper entries.

Long-term Projections

We will explore further the use of @Risk in a fish population dynamics model developed to evaluate the outcome of harvest control rules (HRCs) in the context of the Precautionary Approach. In particular, the spreadsheet can be used to mimic HCRs under the ICES and NAFO PA frameworks, or simply to evaluate constant F-scenarios. It also permits to account for fishing mortality resulting from by-catch in periods of moratorium.

A description of the model algorithm is given in Annex 1. Additional examples using this model are provided in Rivard *et al.* (1999a and 1999b).

The model is contained in the Excel spreadsheet "PA-HRCs.xls". The use of @Risk in combination with this model allows someone to specify uncertainty in initial conditions of the state variables and in certain population dynamic parameters (we focus here on the definition of the stock-recruit relationship). The resulting model provides a framework to calculate the probability of achieving limits or targets in the simulation years, to calculate the time it takes to reach these targets and to evaluate other elements of interest to managers (e.g. number of closures after re-opening, recovery time).

Using this model, we will illustrate the use of @Risk to simulate the effect of various harvest control rules. In doing so, we will take the following steps:

1. Select and define the Precautionary Approach framework.
2. Input abundance estimates and define their distributions.
3. Input historical data on the stock (to relate the past to the future).
4. Select/define the stock-recruit relationship.
5. Run simulations/scenarios.

The @Risk distributions commonly used in such a model would be

- LogNorm (mean, standard deviation)
- LogNorm2 (mean of corresponding normal dist., standard deviation of normal)
- Duniform ({X_1, X_2, …, X_n }), i.e. discrete uniform distribution with n possible outcomes having equal probability of occurring.
- SIMTABLE ({X_1, X_2, …, X_n }), where the X_i are a list of values to be used in each of a series of simulations.

If you have not already done so, load the "PA-HRCs.xls" Excel spreadsheet now.

1. **Select and define the Precautionary Approach framework**

The model simulates the response of the stock to fixed levels of fishing mortality or to specify harvest control rules in relation to a PA framework. Three PA frameworks are already programmed: the ICES PA Framework, the NAFO PA Framework and a general framework allowing more flexibility in specifying harvest control rules in relation to PA reference points (Fig.1). These frameworks are pre-defined in cells E10-H19. To enable one option, copy the relevant cells to cells C10-C19. For example, to enable the constant F option,

36. In the Excel file "PA-HRCs.xls":
37. Select the "Input" tab.
38. Copy cells G10-G19 to C10-C19.
39. See how the PA framework graph changes to reflect the selection.

The constant F option uses a special @Risk function, SIMTABLE(), allowing someone to specify a list inputs to be used sequentially in a series of simulations, i.e. simulations at various fishing mortality levels in our case. See the formula in cell C10.

40. If not already loaded, load @Risk Version 4.0.
41. Select the "Simulation Settings: icon on the @Risk Toolbar.
42. In the "# iterations" box, enter 40.
43. In the "# simulations" box, enter 10.
44. In the "Each Iteration" section, select "Update display".
45. Select the OK button.
46. Select the "Calc" tab.
47. Select the cell AS329 (corresponding to the yield in the last year of the projection.
48. Select "Add Output" on the @Risk Toolbar.
49. Select the "Monitor" tab.
50. Select the "Start Simulation" icon on the @Risk Toolbar.

You will see in the @Risk-Results Screen that 10 simulation have been run, each with a different value for fishing mortality, as listed in cell C10 of the "Input" sheet.

Discussion:

If someone assumes that "equilibrium" has been reached in that year, the results of this simulation essentially give an approximation of the underlying production curve, with its confidence intervals. By declaring the biomass, fishing mortality and yield as Ouput to @Risk, you can generate the Yield/F graphs and Yield/biomass graphs typical of production analyses.

2. **Input abundance estimates and define their distributions**

For simulating the error in the estimation of the initial stock size, the initial population size will be sampled with @Risk from a log-normal distribution. Other distribution could be used, depending of the origin of the estimates of the initial stock size. Input values for the projections are given in Table 1.

NOTE: *To be consistent with projections made in ADAPT, the log-normal distribution should have a mean equivalent to the bias-corrected estimate (on the linear scale). The standard deviation of the log-normal distribution is to be taken as the standard error of the stock size estimate on the linear scale.*

51. In the Excel file "PA-HRCs.xls" (re-load this sheet to ensure that you have it in its original form):
52. Select the "Input" tab.
53. Cells E45-E65 contain the initial estimates of stock size.
54. Cells F45-F65 contain the corresponding C.V.
55. Cells H45-H65 contain the weight-at-age, mid-year.
56. Cells I45-I65 contain the weight-at-age, start of year.
57. Cells J45-J65 contain the partial recruitment to be applied to the fishing mortality.
58. Cells K45-65 contain the maturity at age.
59. Cells L45-65 contain 0 or 1 to indicate which ages are to be used in calculating the mean F (to generate the values needed for certain scenarios).

3. **Input historical data on the stock**

60. In the Excel file "PA-HRCs.xls".
61. Select the "Input" tab.
62. Cells C75-C115 contain the fishing mortality for the years specified.
63. Cells D75-D115 contain the Stock Spawning Biomass (SSB).
64. Cells E75-E115 contain the Stock Spawning Numbers (SSN).
65. Cells F75-F115 contain the recruits.
66. Cells G75-G115 contain the population size (total numbers).
67. Cells H75-H115 contain the biomass (total weight).
68. Cells I75-I115 contain the total yield.
69. Cells J75-J115 contain the total catch, in numbers.

Historical data are listed in Table 2. These are needed for graphical display and, under certain scenarios, could be needed for setting up the re-sampling of the historical SSB-recruit observations.

Discussion:

These entries should be consistent with the estimates of initial stock size, e.g. use bias-corrected estimates if the initial stock size estimates have been bias-corrected. Also, typically, the historical SSB-recruit pairs are expected to be correlated with estimates of initial stock size. For more realistic simulations, taking such correlation into account may be necessary. This could be done in various ways (e.g. correlation calculated from bootstrap results or direct re-sampling of bootstrap results) but this could become quite complex and such exploration is beyond the scope of this tutorial.

4. **Select/define the stock-recruit relationship**

Long-term simulations must make assumptions on the dynamics linking recruitment to the stock spawning biomass. Long-term simulations are very sensitive to the characteristics of the spawner-recruit description. Often, recruitment and spawning stock size are only weakly related.

Many authors have suggested various ways to capture both the dynamics and the uncertainties of the recruitment process by re-sampling the recruit-SSB scatter points. In this spreadsheet, one option available is to split the observed range of SSB into quartiles and to resample the observed recruitment within these quartiles. Since this approach is based on re-sampling observations, it does not require making assumptions about the recruitment probability density function (pdf). Depensation at lower levels of SSB, varying degrees of compensation and the variability of the response of recruitment to SSB levels typically observed make it particularly difficult to derive functional relationships that are convincing. The benefit of non-parametric descriptions of stock-recruitment relationships is that they are able to capture the dynamics of the recruitment process without requiring explicit assumptions about the shape of the relationship. One requirement, however, is that the dynamics has been captured in the range of observations previously observed.

Other options for the stock recruit relationship are 1) "stationary" recruitment, i.e. recruitment assumed to be coming from a log-normal distribution with a given mean and standard deviation and 2) recruitment assumed to be coming from a Beverton-Holt relationship with an error term.

To select the desired option for the stock-recruit relationship.

70. In the Excel file "PA-HRCs.xls":
71. Select the "Input SR" tab.
72. Adjust the parameters for the model to be used and select the desired model by clicking on the appropriate "Select this S/R Model" button. In our case, we will use the default (re-sampling the observations), so there is no need to activate any of the buttons at this stage.
73. Select the "Calc" tab.
74. Go to cells I19-AS19 to ensure that the proper formulas have been transferred to these cells.

    NOTE that you may have to adjust these formulas so that the SSR and recruitment are lagged properly.

If the "re-sampling the data points" option has been selected, you will need to make additional adjustments to ensure that the quartiles for re-sampling recruitment are defined properly. A working area (cells A459-S526) is provided at the bottom of the "Calc" sheet to define these quartiles. Follow the instructions in this area. Note that the re-sampling of the observations is done through the @Risk function RiskDuniform() [see the formula in cell I19].

5. **Run simulations/scenarios**

To illustrate the use of such a model, we will run a simulation using the NAFO PA framework. Our interest will be the impact of this scenario on the Stock Spawning Biomass and Yield.

75. Load the original Excel file "PA-HRCs.xls" to ensure that default values are defined properly for this tutorial.
76. Select the "Input" tab.
77. Select the NAFO PA framework by copying cells G10-G19 to C10-C19.
78. See how the PA framework graph changes to reflect the selection.
79. If not already loaded, load @Risk Version 4.0.
80. Select the "Simulation Settings: icon on the @Risk Toolbar.
81. In the "# iterations" box, enter 100.
82. In the "# simulations" box, enter 1.
83. In the "Each iteration" section, select the "Update display" option.
84. Select the OK button.
85. Select the "Calc" tab.
86. Select the SSB for 1999 to 2036 by selecting the cells H-281-AS281.
87. Select "Add Output" on the @Risk Toolbar.
88. You will be prompt to "Enter a name for this output range:": Enter "SSB".
89. Select the Yield for 1999 to 2036 by selecting the cells H-329-AS329.
90. Select "Add Output" on the @Risk Toolbar.
91. You will be prompt to "Enter a name for this output range:": Enter "Yield".
92. Select the "Monitor" tab (the Monitoring Windows are also illustrated in Fig. 2).
93. Select the "Start Simulation" icon on the @Risk Toolbar.

The simulation will start and the results reported in the @Risk Results window.

94. In the @Risk Results Widow:
95. Select the Stock Spawning Biomass for 2010 in the left hand-side explorer.
96. Select "Insert / Graph / Histogram" from the Menu. A histogram representing the distribution of the biomass for 2010. See how individual simulation results stand in relation to the biomass limit value of 60 000 t.
97. To see a graph of the distribution of SSB for all years in the simulation, select the "Range Summary" tab above the graph. A graph will appear showing the spread of SSB for each year of the simulation.

How simulation results stand in relation to "Target values" can be investigated further with @Risk. The probability of achieving a specific target or outcome can be calculated using the

98. In the @Risk Results Widow:
99. Select the "Summary Statistics" Window.
100. In the "x1" column, enter "60000" in the SSB/2010 row.
101. See how the corresponding probability adjusts to your entry.
102. When a range of output has been specified, someone can get time trends in the probability of meeting the target. For instance, in the "x1" column, enter "60000" in the SSB/1999 row.
103. While your are still pointing at this cell, extend your selection so as to include the entire range of SSBs. Use the "Fill Down" command to copy your entry (i.e. "60000") to all rows corresponding to the SSB range.
104. See how the corresponding probability adjusts to these entries. In essence, you now have the probability of simulation results being below the biomass limit for each year of the simulation.

As an exercise, repeat the preceding steps to calculate the probability of returning to an historical yield of 25000 t.

Harvest Control Rules

Harvest control rules are, in essence, rules that dictate the application of a fishing mortality in a given projection year. What triggers the application of a given fishing mortality level is where the current fishing mortality and Stock Spawning Biomass stand in relation to reference points.

You can define your own rules and test their impact using a spreadsheet such as the one provided here. In the "Calc" sheet, rows 332–340 act as placeholders for the rules that you wish to investigate. The rules pre-programmed here have been designed for the purpose of this tutorial to illustrate various ways of programming harvest control rules under the General PA Framework. If you use this spreadsheet as a template for your own simulations, you will have to put in these rows the HRCs that you wish to test. To illustrate the process that you have to follow, we describe below a decision rule to control harvest, which is based on six rules that can be triggered when SSB_t and F_t values are within predefined ranges delimited by reference points.

The reference points used as triggers for various actions are as follows:

Symbol	Definition
F_{lim}	Fishing mortality limit
B_{lim}	Spawning Biomass limit
B_{buf}	Buffer for Spawning Stock Biomass (SSB); also the B_{pa} in the Ices Framework.
F_{buf}	Buffer for fishing mortality, also the F_{pa} in the Ices Framework.
F_{closed}	Fishing mortality when $SSB<B_{lim}$; typically, this would correspond to the fishing mortality resulting from a bycatch in other fisheries.
B_{tr}	Spawning Stock Biomass target
F_{atBbuf}	Maximum fishing mortality allowed at B_{buf}
F_{tr}	Target fishing mortality

For each year of the projection, six levels of fishing mortalities are calculated as potential candidates for selection. These six possible levels are as follows [note that the equations given follow the notation for specifying arguments in an Excel IF() function]:

Rule 1:

$$F_1 = \text{If } (F_{tr}<F_{closed} , F_{tr}, F_{closed})$$

Rule 2:

$$F_2 = \text{If } ((F_{tr}<(F_{closed}+((F_{atBbuf}-F_{closed})*(1-((B_{buf}-SSB_t)/(B_{buf}-B_{lim})))))),\ F_{tr},$$
$$(F_{closed}+((F_{atBbuf}-F_{closed})*(1-((B_{buf}-SSB_t)/(B_{buf}-B_{lim}))))))$$

Rule 3:

$$F_3 = \text{If } ((F_{tr}<(F_{atBbuf}+((F_{buf}-F_{atBbuf})*(1-((B_{tr}-SSB_t)/(B_{tr}-B_{buf})))))), F_{tr},$$
$$(F_{atBbuf}+((F_{buf}-F_{atBbuf})*(1-((B_{tr}-SSB_t)/(B_{tr}-B_{buf}))))))$$

Rule 4 (progressive reduction in F desired when $SSB_t>B_{tr}$):

$$F_4 = \text{If } (F_{t-1}>F_{lim}, (F_{t-1}-((F_{t-1}-F_{lim})*\text{PercentRule})),$$
$$\text{If } (F_{t-1}>F_{buf} , F_{buf} ,$$
$$F_{buf}))$$

Note that Rule 4 is used to allow a progressive reduction of the fishing mortality estimated for the previous year towards F_{lim}. The estimate of fishing mortality for the previous year, say F_{t-1}, is assumed to be subject to an estimation error and, as such, is taken from a log-normal distribution with mean F_{t-1} (the F applied to year t-1) and standard deviation calculated from the coefficient of variation provided in the "input" sheet. The coefficient "PercentRule" is a decimal value between 0 and 1 representing the proportion of the difference between F_{t-1} and F_{lim} to be applied to the current fishing mortality to reduce it towards F_{lim}.

Rule 5 (applied when PrecentRule = 0, $F_{tr} > F_{buf}$ and $SSB_t > B_{tr}$):

$$F_5 = F_{tr}$$

Rule 6 (applied when PrecentRule = 0, $F_{tr} <= F_{buf}$ and $SSB_t > B_{tr}$):

$$F_6 = \text{If}\,(F_{t-1} > F_{lim}\,,\, F_{lim}\,,\; \text{If}\,(\,F_{t-1} > F_{buf}\,,\, F_{buf}\,,\; F_{tr}\,)\,)$$

Which "rule" is applied in any given year t depends upon the following decision rule:

$$F_t = \text{If}\,(SSB_t{<}B_{lim}\,,\, F_1,\; \text{If}\,(SSB_t{<}B_{buf}\,,\, F_2,\; \text{If}\,(SSB_t{<}B_{tr}\,,F_3,\; \text{If}\,(\,\text{PercentRule} > 0\,,\, F_4,\; \text{If}\,(F_{tr}{>}F_{buf}\,,\, F_5,\; F_6)))))$$

Note that the decision rule implemented here is solely intended for the purpose of this tutorial. If this spreadsheet is used as a template for particular case studies, you should ensure that the functions enabled create the decision rule that is suitable for your situation. Most applications will require adjustments/modifications to the harvest control rules presented here.

Time trajectories for fishing mortality, recruitment, stock abundance and biomass, and yield are plotted in the "Time Graphs" sheet (see also Fig. 3). In a typical simulation, thousands of trajectories are obtained through Monte-Carlo re-sampling. The @Risk interface provides the functionality required to monitor the probability profiles for any variable of interest over the projection horizon. When combined with the functionality provided by the Excel statistical functions, it also provides the means to monitor the probability profiles for derivatives of the results (e.g. to measure the variability of the projections over a given time horizon, the mean level of a variable over a given timeframe, etc).

Discussion:

The current model accounts for uncertainty in implementation of the harvest control rules (i.e. fishing mortality actually realized) only when the SSB_t is $>B_{tr}$. How would you change this model to account for uncertainty in the estimation of SSB_t, which is also used to trigger harvest control rules? How would you change the model to take into account uncertainty in implementing the decision rule itself?

You may also wish to take into account of uncertainty in other population parameters, such as those controlling growth. For instance, how would you model stochastic process for growth?

How would you model regime shifts, i.e. shifts in key population dynamics parameters? Are there other ways to account for assessment and implementation uncertainty? How would you change this model to account for correlated error between certain variables?

Limitations of Long-term Projections

Long-term projections make a number of assumptions on the "realization" of key population parameters in future years. While projection models can be made to account for some of the uncertainties, they rarely capture all possible outcomes. Nevertheless, a well-designed model could be useful for evaluating the response of a stock to various exploitation patterns or regimes. As all sources of uncertainty are rarely captured, actual trajectories may deviate substantially from the model results, even when these are expressed in terms of probabilities. For this reason, when long-term projections are used to investigate the impact of various approaches, the results should be interpreted in relative terms (i.e. in relation to other approaches or scenarios) rather than in absolute terms.

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TABLE 1. Stochastic projections require as input the initial estimate of stock abundance and its standard error, as well as data on weights-at-age, partial recruitment and maturity. In addition to these, the historical SSB-recruit pairs are required (see Table 2).

	Abundance			Weight (kg)		Partial	Maturity
Age	Estimate 1999	C.V.	Std Err.	Mid-year 1972–97	Start of year 1972–97	recruitment 1959–97	(proportion) 1975–97
3	113	0.66	74.6	0.55	0.42	0.20	0.00
4	113	0.48	54.2	0.92	0.74	0.64	0.02
5	437	0.40	174.8	1.42	1.15	0.97	0.13
6	297	0.36	106.9	2.15	1.79	1.00	0.46
7	136	0.32	43.5	3.12	2.61	1.00	0.83
8	64	0.35	22.4	4.45	3.71	1.00	0.97
9	394	0.33	130.0	6.42	5.75	1.00	1.00
10	568	0.32	181.8	8.00	7.54	1.00	1.00
11	62	0.33	20.3	8.99	8.17	1.00	1.00
12	44	0.40	17.6	10.90	11.09	1.00	1.00
13	10	0.40	4.0	10.53	10.35	1.00	1.00
14	1	0.40	0.4	10.89	10.71	1.00	1.00
15				11.28	11.08	1.00	1.00
16				11.67	11.47	1.00	1.00
17				12.08	11.87	1.00	1.00
18				12.50	12.29	1.00	1.00
19				12.94	12.72	1.00	1.00
20				13.39	13.16	1.00	1.00
21				13.86	13.62	1.00	1.00
22				14.35	14.10	1.00	1.00
23				14.85	15.11	1.00	1.00

TABLE 2. Historical data on fishing mortality, spawning abundance and biomass, total stock abundance and biomass, recruitment, and yield. The recruitment process is simulated by re-sampling the SSB-recruit pairs within SSB-quartiles.

		Spawning stock		Total stock			
Year	Fishing mortality	Abundance (#)	Biomass (tons)	Abundance (#)	Biomass (tons)	Recruits (#)	Yield
1959	0.428	30617	87921	207010	206497	53067	64370
1960	0.412	27764	74628	190698	191146	52090	79677
1961	0.506	30139	73170	200419	183688	81045	72724
1962	0.296	26755	70048	237003	187355	106515	34984
1963	0.555	31525	77503	257783	225337	77456	69742
1964	0.282	37335	84493	294232	253676	110562	64461
1965	0.655	46115	110168	352275	287897	160052	99187
1966	0.981	39507	104120	453470	338652	207114	108919
1967	0.829	35654	87556	492097	395438	181079	226784
1968	0.842	31775	78821	358255	320412	99509	165511
1969	0.571	25133	67143	286634	242353	126175	117705
1970	0.556	25942	69411	256537	232731	79267	111561
1971	0.603	28963	76002	249719	241423	83222	126296
1972	0.677	26818	73505	196905	198393	61009	103374
1973	0.515	19817	65822	147611	173992	34539	80429
1974	0.991	18636	62841	100666	130332	36122	73389
1975	1.617	9729	31367	65444	62800	22725	44174
1976	0.386	4208	10680	61495	43083	26976	24283
1977	0.581	3512	11278	77826	56494	44648	17604
1978	0.248	5235	14953	97205	80937	40875	14718
1979	0.326	10183	23678	88377	99809	17069	27851
1980	0.184	14968	37512	76327	101039	19361	19991
1981	0.238	24986	69035	81762	128589	27015	24344
1982	0.293	22146	82581	81045	148790	21326	31605
1983	0.219	21625	84671	92942	164147	34672	28819
1984	0.250	22913	87284	109541	173627	40710	27103
1985	0.358	21060	82186	113844	173605	31807	36899
1986	0.388	16555	77906	86423	148619	8613	50645
1987	0.352	19567	80815	60946	127221	6332	41619
1988	0.573	15521	51035	50823	86929	12464	43150
1989	0.516	14498	49712	40531	71981	12326	33215
1990	0.601	8088	36672	28076	54449	4902	28846
1991	0.936	5506	27742	16331	36585	5180	29454
1992	0.631	3107	11717	21875	23202	13646	12752
1993	0.696	2061	5222	16185	11639	5984	10646
1994	0.335	1740	2759	8207	6851	540	2702
1995	0.013	2162	3204	3552	4346	331	172
1996	0.025	2424	4544	3326	5281	568	174
1997	0.057	2159	4807	3287	5533	641	442
1998	0.068	1941	5893	2648	6479	125	150
1999		1732	6282	2061	6414	87	

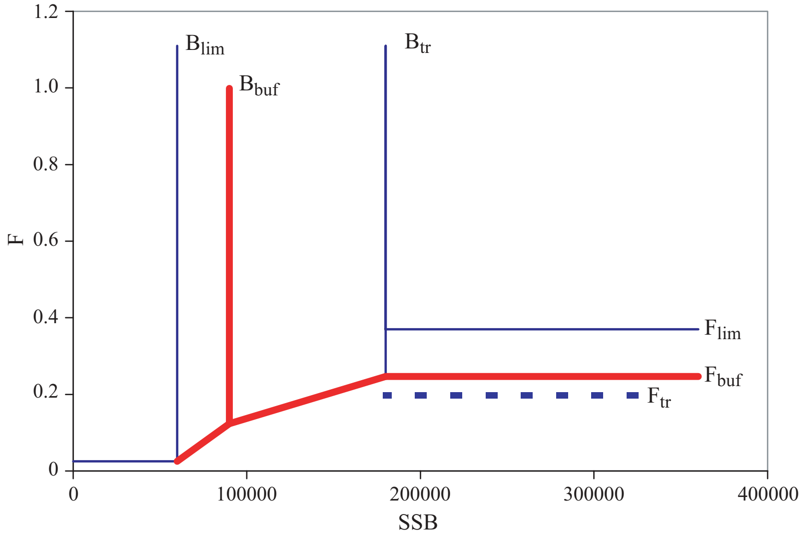

Fig. 1. Generalized framework for a precautionary approach. Controls are provided in terms of a fishing mortality limit (F_{lim}), a spawning biomass limit (B_{lim}), a buffer for fishing mortality (F_{buf}), a buffer for spawning biomass (B_{buf}) and a spawning biomass target (B_{tr}). The impact of by-catch due to fishing on other species can be evaluated by specifying a fishing mortality level below the biomass limit. Also, as separate control rules can be specified above and below B_{buf}, the generalized framework can be used to mimic the features of the ICES or the NAFO precautionary approach frameworks.

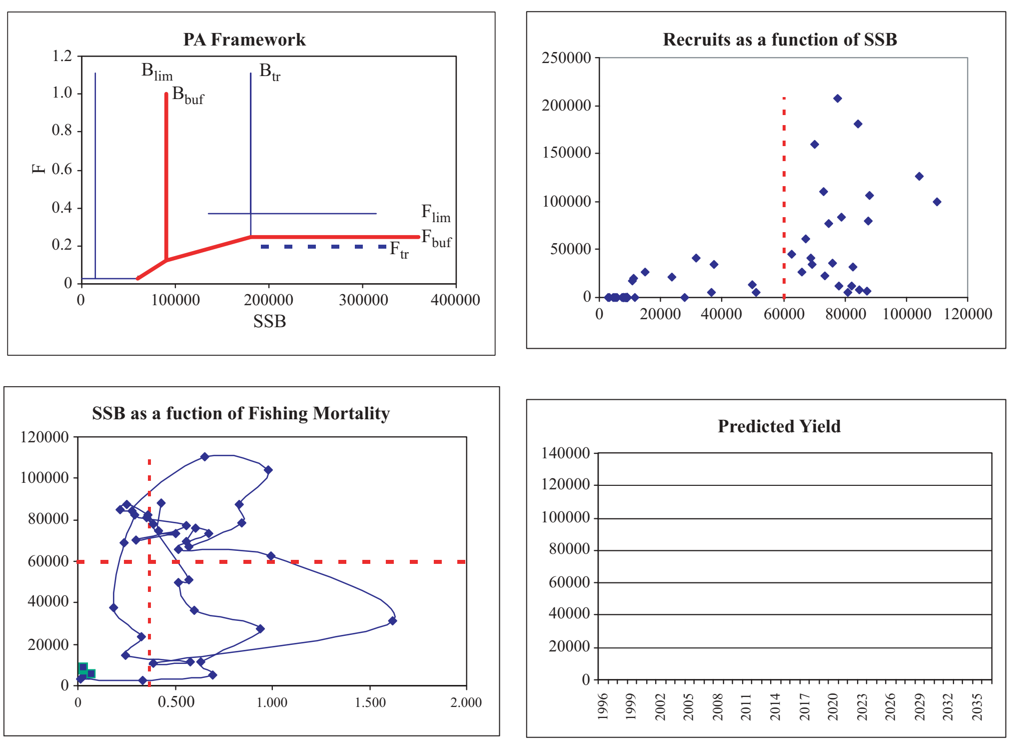

Fig. 2. "Windows" to monitor the simulations. As the simulation proceeds, the stock and fishery trajectories are displayed in these windows to monitor its progress.

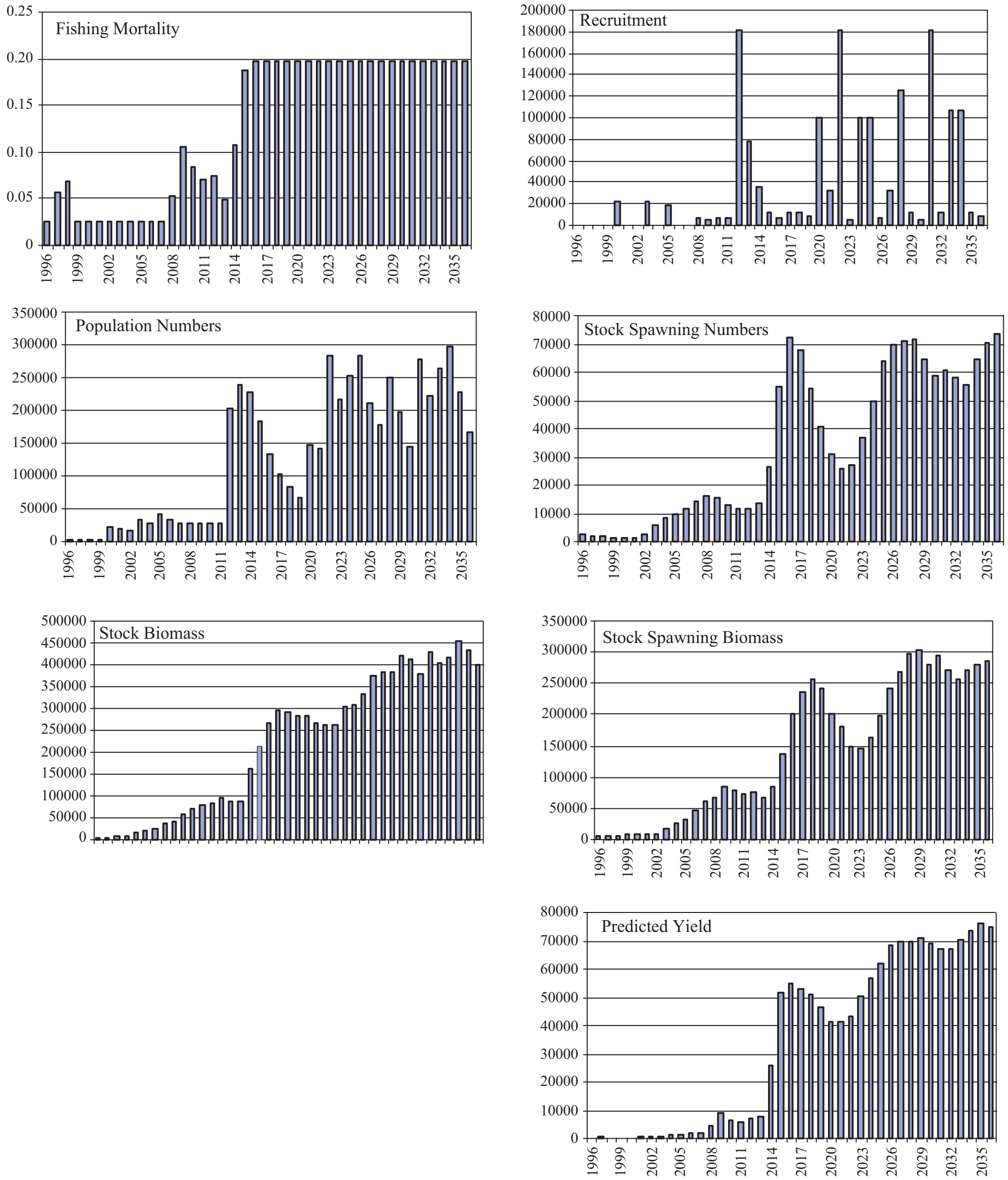

Fig. 3. Time trajectory for fishing mortality, recruitment, stock numbers and biomass (spawning and total), and yield. Represented here are the results for only one of the replicates realized during the Monte-Carlo simulation. In a typical simulation, thousands of replicates are generated.

Annex 1. Population Dynamics Algorithm

Notation. The subscripts *i* and *t* are used below to identify an entity at a specific time while the Greek letter ι identifies the interval between *i* and *i+1*, and τ, the interval between *t* and *t+1*.

The input information required for the simulation consists of:

$N_{i,t}$	Population numbers at age i, for the first year of your projection. Estimates of population numbers and their variances, are typically obtained from age-structured analyses of historical data on catch information and survey indices.
$W_{i+0.5}$	Mid-year estimates of weight-at-age, in kilograms.
W_i	Beginning-of-year estimates of weight-at-age, in kilograms.
d_i (i=3, …, 23) :	a value, between 0 and 1, indicating the proportion of fish in age-group i which are have attained maturity.
r_ι	"Partial recruitment" coefficients. These are values, between 0 and 1, indicating the proportion of fishing mortality to be applied to age-group i,i+1.

The instantaneous rate of natural mortality, M, is assumed to be constant for all ages and all years included in the simulations.

Fishing strategies. The evaluation of harvest control laws requires the application of a target fishing mortality for each year considered in the projection, say F_τ. The calculation of the instantaneous fishing mortalities at each age in each year-period $_\tau$ are given by:

$$F_{\iota,\tau} = r_\iota F_\tau$$

where r_ι are the "partial recruitment" coefficients.

Population numbers. The number of fish at age i in year t is given by:

$$N_{i,t} = N_{i-1,t-1} \exp(-Z_{\iota-1,\tau-1})$$

where

$$Z_{\iota-1,\tau-1} = F_{\iota,\tau} + M_{\iota,\tau}$$

Fish are assumed to leave the exploited stock beyond the oldest age-group. For each year of the projection, the numbers in the first age-group considered are set equal to the recruits R_t. The recruits in each year come from a stock recruit relationship, which is to be specified by the user.

The total number of fish is given by:

$$N_{\bullet,t} = \Sigma N_{i,t}$$

where the summation is over all ages *i*. Similarly, the total number of mature fish in year t is given by $\Sigma\ d_i N_{i,t}$, where the summation is over ages.

Population biomass. The age-specific biomass at the beginning of each year is given by:

$$B_{i,t} = W_{i,t} N_{i,t}$$

The total biomass is given by:

$$B_{\bullet,t} = \Sigma \; B_{i,t}$$

where the summation is over all ages. Similarly, the total biomass of mature fish at the beginning of each year is given by $\Sigma \; d_i \, B_{i,t}$. The average biomass (age-specific) for each year is given by:

$$B_{i,t} = W_{i+0.5} \, N_{i,t} \; (1 - \exp (- Z_{i,\tau})) / Z_{i,\tau}$$

Catch in numbers. The catch at age in each year is given by:

$$C_{l,\tau} = F_{i,\tau} \, N_{i,t} \; (1 - \exp (- Z_{i,\tau})) / Z_{i,\tau}$$

The total number of fish in the catch in any given year is given by:

$$C_{\bullet,t} = S \, C_{i,\tau}$$

Yield. The age-specific yield is calculated in any given year as:

$$Y_{i,\tau} = W_{i+0.5} \, C_{i,\tau}$$

The total yield in any given year is given by:

$$Y_{\bullet,t} = S \, Y_{i,\tau}$$