SSC DEFAULT REBUILDING ANALYSIS

Technical specifications and User Manual

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TECHNICAL OVERVIEW

1. INTRODUCTION

The rebuilding analysis software performs the calculations developed by the Scientific and Statistical Committee of the Pacific Fishery Management Council (SSC, 2001, 2005, 2008, 2012). The key steps in this process are:

a) Determine the maximum allowable rebuilding period (if this is not pre-specified by the user).
b) Determine the (generally constant) level of fishing mortality (or catch) that satisfies specifications regarding the probability of recovery within the maximum allowable rebuilding period.
c) Conduct projections for various user-specified time-trajectories of fishing mortality, spawning potential ratio or of catch (harvest strategies) to evaluate the trade-off between the annual catches and the rate of recovery to the target biomass.
d) Display various output statistics.

The modifications made to the software with each update are listed in Appendix A.

1.1 BASIC DYNAMICS

1.1.1 Dynamics equations

The dynamics of the population are modeled using an age- and sex-structured population dynamics model. The basic dynamics model depends on whether or not the oldest age (age $a_{\max}$) is treated as a plus-group (Equations 1a and 1b respectively):

$$N^s_{y,a} = \begin{cases} 0.5\,R_y & \text{if } a = a_{\min} \\ N^s_{y-1,a-1}\, e^{-Z^s_{y-1,a-1}} & \text{if } a_{\min} < a < a_{\max} \\ N^s_{y-1,a_{\max}-1}\, e^{-Z^s_{y-1,a_{\max}-1}} + N^s_{y-1,a_{\max}}\, e^{-Z^s_{y-1,a_{\max}}} & \text{if } a = a_{\max} \end{cases} \tag{1a}$$

$$N^s_{y,a} = \begin{cases} 0.5\,R_y & \text{if } a = a_{\min} \\ N^s_{y-1,a-1}\, e^{-Z^s_{y-1,a-1}} & \text{if } a_{\min} < a \end{cases} \tag{1b}$$

where $N^s_{y,a}$ is the number of animals of sex *s* (male m and female f) and age *a* at the start of year *y,*

$Z^s_{y,a}$ is the total mortality on animals of sex *s* and age *a* during year *y*:

$$Z^s_{y,a} = M^s_a + F_y \sum_f S^{f,s}_a\, \eta^f_y \tag{2}$$

M^s_a is the instantaneous rate of natural mortality on animals of sex *s* and age *a*,

$S^{f,s}_a$ is the selectivity by fleet *f* for animals of sex *s* and age *a*,

F_y is the fully-selected (i.e. $\sum_f S_a^s \eta_y^f \to 1$) fishing mortality during year y,

η_y^f is a user-specified relative weighting factor for the fleets during year y (note that the age-at-maximum selectivity need not be the same for all of the fleets); by definition $\sum_f \eta_y^f = 1$,

R_y is the recruitment (both sexes) during year y, and

$a_{\min}$ is the lowest age-class considered in the model.

1.1.2 Initial conditions

The numbers-at-age at the start of the first year of the rebuilding period (defined here as the year for which an ACL is needed – in principle, the resource may already have a rebuilding plan and there may be a need to modify it based on new information), y_{start}, may differ from those at the start of the last year of the assessment, y_{init}. The numbers-at-age at the start of year y_{start} are obtained by projecting from the start of year y_{init} (for which the numbers-at-age are available from the assessment) to the start of year y_{start}. This projection involves removing the known catches for the years y_{init} to $y_{\text{start}} - 1$. Similarly, the numbers-at-age at the start of the first year that the ACL could have been zero under the rebuilding plan (usually one year after the stock was declared to be overfished), y_{decl} (or y_{init} if $y_{\text{init}} < y_{\text{decl}}$) needs to be provided. The year for which this age-structure is provided is referred to as y_{init}^0. If $y_{\text{init}}^0 < y_{\text{decl}}$ the population is projected to year y_{decl} by removing the known catches for the years y_{init}^0 to y_{decl}-1.

1.1.3 Parameterization

The values for the numbers-at-age at the start of years y_{init} and y_{init}^0, natural mortality-at-age (by sex), weight-at-age (by fleet and sex), selectivity-at-age (by fleet and sex), and the parameters of the stock-recruitment relationship can either be set equal to the best estimates for these quantities or the projections can be based on a set of alternative parameter vectors (each parameter vector containing values for the required numbers-at-age, natural mortality-at-age, weight-at-age and selectivity-at-age). Conducting projections using a set of alternative parameter vectors allows the impact of parameter uncertainty on the rebuilding analysis results to be evaluated. The alternative parameter vectors can be obtained using, for example, bootstrapping, Bayesian methods or the 'numerical delta' method (see Patterson *et al*. (2001) for an overview of these techniques). Section 1.4 provides additional information regarding how parameter uncertainty is taken into account when conducting a rebuilding analysis.

1.1.4 Recruitment

Three options are available for generating future recruitment: random recruitment, random recruits per spawner, and the use of a stock-recruitment relationship. The first option involves selecting a recruitment at random from those for a pre-specified set of historical years and setting the recruitment for future year y equal to that recruitment. The second option involves selecting a recruitment, R_{y*}, at random from those for a pre-specified set of historical years, calculating the recruits per spawner ratio for that year, i.e. $\tilde{R}_{y*} = R_{y*} / SB_{y*-a_{\min}}$ where SB_y is the spawning output at the start of year *y*. The recruitment for year *y* is then $\tilde{R}_{y*}\, SB_y$ where SB_y is defined by the equation:

$$SB_y = \sum_{a=a_{mat}}^{a_{\max}} \phi_a\, N^f_{y,a} \tag{3}$$

where ϕ_a is fecundity as a function of age, and

a_{mat} is the minimum age-at-maturity (the greater of $a_{\min}$ and 1 – animals of age 0 cannot be mature).

The final option (stock-recruitment relationship) involves generating future recruitment using either a Beverton-Holt (Equation 4a) or a Ricker (Equation 4b) relationship:

$$R_y = \frac{SB_{y-a_{\min}}}{\alpha + \beta\, SB_{y-a_{\min}}} e^{\varepsilon_y - \sigma_r^2/2}; \quad \varepsilon_y = \rho\varepsilon_{y-1} + \sqrt{1-\rho^2}\,\eta_y \qquad \eta_y \sim N(0;\sigma_r^2) \tag{4a}$$

$$R_y = \alpha\, SB_{y-a_{\min}}\, e^{-\beta SB_{y-a_{\min}}} e^{\varepsilon_y - \sigma_r^2/2}; \quad \varepsilon_y = \rho\varepsilon_{y-1} + \sqrt{1-\rho^2}\,\eta_y \qquad \eta_y \sim N(0;\sigma_r^2) \tag{4b}$$

where α, β are the parameters of the stock-recruitment relationship (determined from the virgin recruitment and the "steepness" of the stock-recruitment relationship),

ρ is the extent of temporal auto-correlation in the residuals about the stock-recruitment relationship, and

σ_r is the standard deviation of the logarithms of the multiplicative fluctuations in recruitment.

The software includes the feature to replace the random selection process by a process in which the recruitment (or the recruits per spawner ratio) used to generate future recruitment is pre-specified.

1.1.5 Determining annual fishing mortality

The annual fishing mortality, F_y, is either pre-specified (i.e. $F_y = F_{\text{ref}}$), determined by a transitional policy, or determined by solving the catch equation:

$$C_y = \sum_f C^f_y; \quad C^f_y = \sum_s \sum_{a=a_{\min}}^{a_{\max}} \frac{w^{f,s}_a\, N^s_{y,a}\, S^{f,s}_a\, \eta^f_y F_y}{Z^s_{y,a}} (1 - e^{-Z^s_{y,a}}) \tag{5}$$

where $w^{f,s}_a$ is the (pre-specified) weight of an animal of sex *s* and age *a* when it is caught by fleet *f* (differences in weight-at-age among fleets could be due to differences in the areas fished, to differences in the timing of the fisheries, or to the impact of length-specific selectivity).

Two "transitional" policies are available. These depend on there being a "target" fishing mortality, F_{targ}, which can be considered to be a proxy for F_{MSY} and which is defined as the fishing mortality that reduces spawning output-per-recruit to a pre-specified (x) percentage of its virgin level, i.e.:

$$\sum_{a=a_{mat}}^{a_{\text{last}}} \phi_a \, e^{-\sum_{a'=a_{\min}}^{a-1} (M^{\text{f}}_{a'} + \sum_f S_a^{f,\text{f}} \tilde{\eta}^f F_{\text{targ}})} = x \sum_{a=a_{mat}}^{a_{\text{last}}} \phi_a \, e^{-\sum_{a'=a_{\min}}^{a-1} M^{\text{f}}_{a'}} \tag{6}$$

where a_{last} is $5a_{\max}$ when the analysis incorporates a plus-group and $a_{\max}$ when it does not, and

$\tilde{\eta}^f$ is the split of the fishing mortality among fleets used when calculating the target fishing mortality ($\tilde{\eta}^f$ is taken to be the fishing mortality split for the final year of the projection period).

Restricting the summation to $5a_{\max}$ in Equation (6) will mean that the virgin spawning output will be under-estimated slightly. However, the magnitude of this will be negligible if $a_{\max}$ or M are reasonably high.

The two "transitional" policies are defined as follows:

- Change the level of fishing mortality to F_{targ} when the spawning output exceeds the target for rebuilding of a proportion γ of the (expected) virgin spawning output (i.e. γB_0 where $\gamma = 0.4$ for west coast groundfish species except for flatfish for which $\gamma = 0.25$), i.e.:

$$F_y = \begin{cases} F_{\text{ref}} & \text{if } SB_y < \gamma B_0 \\ F_{\text{targ}} & \text{otherwise} \end{cases} \tag{7}$$

  Note that this option has the disadvantage of discontinuous changes in fishing mortality when the spawning output recovers to the target spawning output.

- Base the fishing mortality rate on a pre-specified control rule (such as the 40-10 rule - see Equation 8) once the spawning output has recovered to γB_0, i.e. the fishing mortality rate is F_{ref} from the beginning of rebuilding period until the spawning output first reaches γB_0 after which it is determined using the pre-specified control rule.

Results are also shown for management based on, F=0, the ACL control rule and on an X-Y control rule (e.g. the 60-20 rule). The OFL control rule sets the catch for year y

using a fishing mortality of F_{targ} while the X-Y rule sets the catch for year *y* using the formula:

$$C_y = \begin{cases} 0 & \text{if } SB_y \le X.B_0 \\ C_y^{ABC} \dfrac{Y\,B_0}{SB_y}\left(\dfrac{SB_y / B_0 - X}{Y - X}\right) & \text{if } X.B_0 < SB_y < Y.B_0 \\ C_y^{ABC} & \text{if } Y.B_0 \le SB_y \end{cases} \quad (8)$$

where C_y^{ABC} is the catch for year *y* based on a fishing mortality of F_{targ} multiplied by the proportional buffer between the OFL and the ABC.

The catch removed from the population may differ the expected catch given the specified harvest strategy due to implementation error. Two options are available regarding implementation error:

1. The actual catch is log-normally distributed about the intended catch, i.e.: $C_y^{\mathrm{Actual}} = C_y^{\mathrm{Intended}} e^{\kappa_y - \sigma_I^2/2};\;\; \kappa_y \sim N(0;\sigma_I^2)$
2. The actual catch is uniformally distributed, ie.: $C_y^{\mathrm{Actual}} = U[\lambda_1 C_y^{\mathrm{Intended}}, \lambda_2 C_y^{\mathrm{Intended}}]$

The user has the option to constrain the catch in any year is not to exceed the Allowable Biological Catch (ABC). The ABC is calculated by multiplying the catch corresponding to the proxy for F_{MSY} (Equation 5) by a "buffer" (see Ralston *et al*. 2011). This option should be exercised when selecting the time-series of expected catches corresponding to some target level, but not when allowance is made for implementation error (otherwise the catch cannot exceed the ABC).

1.2 DETERMINING THE MAXIMUM ALLOWABLE REBUILD PERIOD

The maximum allowable rebuild period, $T_{\max}$, is the number of years beyond year y_{start} to which the pre-specified probability of recovery to $\gamma\, B_0$ applies. It can either be specified by the user or computed based on the guidelines in National Standard 1. If computed internally by the software, $T_{\max}$ is defined as 10 years beyond year y_{decl} if the population can be rebuilt (in the absence of catches) in less than 10 years from the time that a zero catch could have been set under the rebuilding plan, or the time to rebuild in the absence of catches from year y_{decl} plus one mean generation time if the population cannot be rebuilt within ten years. Uncertainty is incorporated in the definition of the maximum allowable rebuild period by accounting for variability in future recruitment (and parameter uncertainty if the projections are based on replicate parameter vectors) and by defining the rebuild period in terms of the time for there to be at least a 0.5 probability that the spawning output exceeds the target level of $\gamma\, B_0$, i.e.:

$$T_{\max} = \begin{cases} 10 + y_{\text{decl}} - y_{\text{start}} & \text{if } \Pr\text{ob}(SB_{10+y_{\text{decl}}} > \gamma B_0) \ge 0.5 \\ T_G + T_{\min} + y_{\text{decl}} - y_{\text{start}} & \text{otherwise} \end{cases} \tag{9}$$

where T_G is the mean generation time,

$T_{\min}$ is the median of the (Monte Carlo) distribution for the lowest year, y, such that $\Pr\text{ob}(SB_{y+y_{\text{decl}}} > \gamma B_0) \ge 0.5$ for $F_y = 0$ for $y \ge 0$, and

y_{start} is the first year of the projection period (i.e. one year beyond the last year for which catches are available); note that, in general, $y_{\text{start}} > y_{\text{decl}}$

The (expected) virgin spawning output, B_0, is defined using the equation:

$$B_0 = 0.5\, R_0 \sum_{a=a_{mat}}^{a_{\text{last}}} \phi_a \, e^{-\sum_{a'=a_{\min}}^{a-1} M^{\text{f}}_{a'}} \tag{10}$$

where R_0 is the virgin recruitment (either a specified value or the arithmetic average of the recruitments for a pre-specified period). The value of $T_{\min}$ is determined by projecting the population from year y_{decl} in the absence of catches (i.e. $F_y = 0$ in Equation 1) and determining the first year in which the constraint $\Pr\text{ob}(SB_{y+y_{\text{decl}}} > \gamma B_0) \ge 0.5$ is satisfied. The generation time, T_G, is defined using the equation:

$$T_G = Round\left(\sum_{a=a_{mat}}^{a_{last}} a\, \phi_a \, e^{-\sum_{a'=a_{\min}}^{a-1} M^{\text{f}}_{a'}} \Big/ \sum_{a=a_{mat}}^{a_{last}} \phi_a \, e^{-\sum_{a'=a_{\min}}^{a-1} M^{\text{f}}_{a'}} \right) \tag{11}$$

1.3 DETERMINING THE REBUILDING STRATEGY

The reference level of fishing mortality (or of constant catch) is selected to satisfy one of the following three equations:

$$z = \text{Prob}(SB_{T_{\max}} > \gamma\, B_0) \tag{12a}$$

$$0.5 = \text{Prob}(SB_{\tau + y_{\text{start}}} > \gamma\, B_0) \tag{12b}$$

$$z = \text{Prob}(SB_{y_{\text{start}}+100} \ge SB_{y_{\text{start}}}) \tag{12c}$$

Equation (12a) chooses the reference level of fishing mortality so that the probability of recovery by year $T_{\max}$ equals a pre-specified value whereas Equation (12b) chooses the reference level of fishing mortality so that the probability of recovery after a (pre-specified) number (τ) of years equals 0.5. The year $\tau + y_{\text{start}}$ is equivalent to T_{target}, the year in which rebuilding is intended to occur with 50% probability. Equation (12c) chooses the reference level of fishing mortality so that the probability that the spawning output in 100 years (year $y_{\text{start}} + 100$) is equal to or larger than the current (year y_{start}) spawning output.

Two alternative definitions for $\text{Prob}(SB_y > X)$ are considered:

- The probability that the spawning output at the start of year *y* exceeds *X*, or
- The probability that the spawning output exceeded *X* any year from year y_{start} to year *y*.

The second definition is clearly less conservative than the first. However, it is designed to consider as "rebuilt" cases in which the population recovers to γB_0 and then subsequently drops below this level. This should be expected to occur if recruitment is highly variable or if a "transition" policy that is designed to stabilize the resource at γB_0 is examined. Although the user can select between the two definitions for $\text{Prob}(SB_y > X)$ when the analysis is based on Equations (12a) and (12b), this is not the case when the analysis is based on Equation (12c) – for this case, the first definition is always used.

1.4 EXTENSIONS FOR MULTIPLE PARAMETERS

Account can be taken of uncertainty about the values for the parameters of the population dynamics model, in addition to uncertainty about future recruitment. The current version of the software allows for uncertainty in: fecundity, natural mortality, selectivity, weight, the relationship between recruitment and spawning output, and numbers-at-age. Taking account of uncertainty about numbers-at-age captures the uncertainty in the present age-structure of the population, the age-structure of the population when the catch could have been first set to zero under the rebuilding plan, historical recruitment, and historical spawning output. Ideally, there should be as many vectors of parameters as there are simulations. However, the number of parameter vectors, N_{par}, is often smaller than the number of simulations, N_{sim}. When this happens, the rebuilding software cycles through the N_{par} vectors as necessary while conducting the N_{sim} simulations (e.g. if there are 1,000 parameter vectors and the analysis is based on 3,000 simulations, each parameter vector will be used three times so that the number of parameter vectors equals the number of simulations).

The process of conducting a rebuilding analysis when there is uncertainty about the parameter values is essentially identical to that outlined above, except:

a) The generation time used when applying Equation 9 is the average generation time over the N_{par} parameter vectors.
b) B_0 is calculated separately for each parameter vector (i.e. average unfished recruitment for the parameter vector multiplied by unfished spawning output-per-recruit for the parameter vector) and recovery for a given parameter vector is defined to be recovery to γB_0 for that parameter vector (rather than, say the average of γB_0 over all the parameter vectors).

c) When fishing mortality is constrained to be less than F_{MSY}, F_{MSY} is first calculated for each parameter vector as the fishing mortality rate corresponding to the spawning output-per-recruit proxy for *MSY* (e.g. $F_{50\%}$ for rockfish) and the maximum of these values is taken as the maximum possible fishing mortality rate. Note that if the projections are based on spawning output-per-recruit, whether uncertainty about the parameters of the model is taken into account or not is irrelevant in terms of defining the maximum spawning output-per-recruit because the F_{MSY} proxy spawning output-per-recruit is the same for all of the parameter vectors (e.g. 50%).
d) $T_{\min}$ is calculated as the lowest year, *y*, such that $\Pr\text{ob}(SB_{y+y_{\text{decl}}} > \gamma B_0) \geq 0.5$ for $F_y = 0$ for $y \geq 0$ where the probability is taken across uncertainty in parameter vectors and future recruitment.
e) When the projections are based on fishing mortality (rather than spawning output-per-recruit), the calculations for the ABC and the X-Y control rules are based on the F_{MSY}'s by parameter vector, i.e. the OFL, ABC and X-Y rule calculations assume perfect information about the F_{MSY} proxy (by analogy with the way these calculations are conducted when there is only one parameter vector).

Note that there is no longer a one-one relationship between fishing mortality and spawning output-per-recruit when allowance is made for parameter uncertainty. This implies, for example, that the catch based on a spawning output-per-recruit of 50% is not the same as calculating $F_{50\%}$ based on the best estimates of the model parameters and calculating the catch for this fishing mortality rate. Similarly, the ACL for a 60% probability of recovery will not be the same for projections based on fishing mortality and on spawning output-per-recruit when account is taken of parameter uncertainty.

1.5 OUTPUT STATISTICS

The key outputs from a rebuilding analysis are the 5th, 25th, 50th, 75th and 95th percentiles for the distributions for each future year of the catch (in total and by fleet – see Equation 5), spawning output (Equation 3) expressed as a fraction of γB_0, recruitment, fishing mortality, exploitable biomass (for the first fleet), and cumulative (discounted) catch for a pre-specified probability of recovery within the maximum allowable rebuilding period. The exploitable biomass for the first fleet, B_t^e, and cumulative catch, $\tilde{C}_y$, are defined as:

$$B_y^e = \sum_s \sum_{a=a_{\min}}^{a_{\max}} w_a^{1,s} \, S_a^{1,s} \, N_{y,a}^s \, e^{-Z_{y,a}^s/2} \tag{13a}$$

$$\tilde{C}_y = \sum_{y=y_{\text{start}}}^{y} C_y \, e^{-\delta(y-y_{\text{start}})} \tag{13b}$$

where δ is an economic discount rate.

In addition to the key outputs, the software also outputs a histogram of the long-term biomass in the absence of fishing (i.e. the B_0 distribution), the histogram of the time to rebuild (from year y_{decl}) in the absence of catches (T_{min} is the median of this distribution), the histogram of the time to rebuild (from year y_{start}) for the pre-specified probability of recovery, the cumulative probability of being recovered as a function of time for the pre-specified probability of recovery, the probability of dropping below the spawning output in years y_{start} and y_{decl}, and the time-trajectory of the probability of being above the target level for a variety of alternative harvest strategies (i.e. alternative choices for z and τ in Equation 12a and 12b).

The default harvest strategy for many west coast groundfish species involves assuming that the fishing mortality at which the spawning output-per-recruit is 30-50% of that in a virgin state, $F_{x\%}$ - where x is a percentage (30-50%) - is a proxy for F_{MSY}. The validity of this assumption has been questioned for some species (e.g. MacCall and Punt, 2001). The software produces estimates of mean and median replacement yield fishing mortality, F_{rep} corresponding the 'best estimate' parameter vector (the fishing mortalities at which the recruits-per-spawner equals the mean recruits-per-spawner and the median recruits-per-spawner respectively). A check should be made to assess whether these F_{rep} values are substantially lower than $F_{x\%}$, as this may indicate that $F_{x\%}$ is a too aggressive harvest strategy. Note that care needs to be taken when interpreting F_{rep} because its expectation depends on the exploitation history of the stock. For example, F_{rep} should be close to 0 if its estimation is based on recruitment and spawning output data for the earliest years of exploitation (Jakobsen, 1993).

The user can replace one of the default harvest strategies by a strategy of their own choosing. The user-defined harvest strategy can involve periods in which the fishing mortality rate (or the spawning output-per-recruit) is pre-specified and others in which the annual catch is pre-specified[1]. Alternatively it can involve values for z and τ in Equations (12a) – (12c) that differ from the values those that are hard-wired into the software.

[1] Note that when account is taken of parameter uncertainty, pre-specifying a fishing mortality rate is not the same as pre-specifying a spawning output-per-recruit unless all of the biological parameters and the selectivity patterns are the same for each alternative parameter vector.

USER' S GUIDE

1. INTRODUCTION

The software consists of two program: a program (REBUILD.EXE), written in FORTRAN and that runs in DOS, that conducts the bulk of the calculations and a spreadsheet SUMMARY.XLS that includes macros that take the output from REBUILD.EXE and produce the summary tables and graphs required by the Scientific and Statistical Committee. An R script has been developed which produces most of these graphs and tables. The input files for REBUILD.EXE should be included in documentation supplied with a rebuilding analysis (see SSC (2012) for the most recent description of the reporting requirements for rebuilding analyses).

2. REBUILD

The program REBUILD.EXE implements the bulk of the calculations required to conduct a rebuilding analysis. It takes as input a file called REBUILD.DAT and produces a file called RES.CSV. The RES.CSV file is the input to the spreadsheet SUMMARY.XLS (or the R script). Therefore, to use REBUILD.EXE, it is necessary to fill in the file REBUILD.DAT.

Warning:

The program REBUILD.EXE expects (with the few exceptions noted below) input in all of the fields in the file REBUILD.DAT, even if the actual application will not be using all of the inputs. Lines in REBUILD.DAT that start with the hash (#) symbol are comments – these are ignored when the program is run. However, the location of these comments is hard-wired into the program and should not be added to or deleted. Doing so will result in the program failing to operate correctly.

2.1 REBUILD.DAT

This section lists each of the sections in REBUILD.DAT and what needs to be provided for each section.

1) Title – enter a title (up to 80 characters) – this title is displayed on the summary spreadsheet.
2) "Number of sexes": Enter "1" or "2" here.
3) "Age range to consider": Enter the lowest and greatest age to be considered in the rebuilding analysis ($a_{\min}$ and $a_{\max}$). The recruitment estimates must apply to age $a_{\min}$, and age $a_{\max}$ may be a plus-group.
4) "Number of fleets": Enter the number of fleets (up to a maximum of 5), n_F, to consider.
5) "First year of the projection (Yinit)": This is the year from which the projection starts (year y_{init}). It will usually be the last year of the most recent assessment.
6) "First year the OY could have been zero": This year (y_{decl}) is the first year for which a zero OY could have occurred under the rebuilding plan (see Section 1.2 for a description of how y_{decl} is related to the maximum allowable rebuild period, $T_{\max}$).

7) "Number of simulations": Enter the number of simulations to conduct. It is recommended that 100 be selected for preliminary (explorative) analyses, but that the final calculations be based on at least 1,000 simulations. Ideally, the number of simulations should be such that increasing this number does not improve the "smoothness" of the plots.
8) "Maximum number of years": Specify the maximum length of the simulation period. Reducing this value should speed up the analyses.
9) 'Conduct projections with multiple starting values". Enter "0" to base the projections on the 'best estimates' for the model parameters. Otherwise the projections are based on a (large) number of alternative sets of model parameters.
10) "Number of parameter vectors". Enter the number of sets of parameter vectors on which to base the projections (if a number other than "0" was entered at input 9). If the number of parameter vectors is less than the number of simulations, the parameter vectors are "recycled" as needed (see Section 1.4).
11) "Is the maximum age a plus group?": Enter "1" if age $a_{\max}$ is to be treated as a plus-group and "2" if all animals are assumed to die at age $a_{\max}$.
12) "Generate future recruitments": Enter "1" to generate future recruitments using historical information on recruitment, "2" to generate future recruitments using historical information on recruits per spawner, "3" to generate future recruitment using a Beverton-Holt stock-recruitment relationship or "4" to generate future recruitment using a Ricker stock-recruitment relationship (see Section 1.1.4 of the technical description).
13) "Constant fishing mortality or constant catch": Enter "1" for the projections to be based on a constant level of fishing mortality or "2" for the projections to be based on a constant catch. The constant fishing mortality may be modified to change over time as the population approaches the target level (see input 32) below and Section 1.1.5 of the technical description).
14) "Fishing mortality based on SPR or F": Enter "1" for the calculations to be based on spawning output-per-recruit or "2" for the calculations to be based on fishing mortality. Note that this specification has little impact on most of the calculations because there is a 1-1 relationship between spawning output-per-recruit and fishing mortality. However, this specification is important if projections are to be conducted based on the results of a previous rebuilding analysis.
15) "Pre-specify the year of recovery". Enter "-1" here if Equation (9) is to be used to calculate the maximum allowable rebuild period, $T_{\max}$. If $T_{\max}$ is not to be calculated using Equation (9), for instance because the value for $T_{\max}$ was set based on an earlier rebuilding analysis, the value of $T_{\max}$ should be provided here.
16) "Fecundity-at-age": Enter the "best estimates" of relative spawning output for each age. Fecundity-at-age should be the same as was used in the assessment and may be weight-at-age, percentage maturity-at-age multiplied by the age-specific number of eggs per mature female, or some other appropriate measure of spawning output depending on what was assumed in the assessment. If allowance is to be made for time-varying fecundity-at-age and weight-at-age, fecundity-at-age for year y_{init} should be entered here.
17) For each sex (females then males), enter the 'best estimates' of weight-at-age and selectivity-at-age by fleet. Note that if the number of sexes is 1, input should be

provided for females and males combined. The weight-at-age provided here should be the weight-at-age in the catch – this is often the weight-at-age in the middle of the year. If allowance is to be made for time-varying fecundity-at-age and weight-at-age, weight-at-age for year y_{init} should be entered here.

18) For each sex (females then males), enter the 'best estimates' of natural mortality-at-age (yr^{-1}) and the number of animals of each age at the start of year y_{init}. Note that if the number of sexes is 1, input should be provided for females and males combined.

19) Age-structure at the start of year Yinit^0": For each sex (females then males), enter the 'best estimates' of the numbers of animals of each age at the start of the year in which the rebuilding plan first could have had an impact on the ACL, y^0_{init}. In general, this year should be the year in which the species / stock was declared overfished. However, it will be a year before y_{decl} if an assessment has not taken place since y_{decl}.

20) "Year Yinit^0": Enter the year to which the previous input relates, y^0_{init}. This input should either be y_{decl} or y_{init} depending on whether an assessment has occurred since y_{decl} or not. An error message is produced if y^0_{init} is neither y_{decl} nor y_{init}.

21) "Number of historical assessment years": Enter the number of years included in the original assessment and on which B_0 and future recruitment may be based.

22) "Historical data": Enter, for each year included in the original assessment, the year, recruitment (both sexes combined), spawning output, whether the recruitment should be included in the calculation of B_0, whether the recruitment should be included in the determination of future recruitment if future recruitment is generated by sampling from past recruitments, and whether the recruits-per-spawner ratio should be included in the determination of future recruitment if future recruitment is to be generated by sampling from past recruits-per-spawner. Each of these types of inputs is entered on a different line.

    A "yes" is indicated by a "1" for the last three questions. Note that entering a "1" in the recruits per spawner row indicates that the recruitment for the year concerned is included in the projections; the recruits-per-spawner ratio for year y is determined by dividing the recruitment for year y by the spawning output for year y-a_{min}. An error message is produced if the spawning output for the last year differs by more than 0.01% from the spawning output obtained by multiplying the initial age-structure by the fecundity-at-age. The last year of the series should be the first year of the projection period (y_{init}, see input 5); if this is not the case an error message is output. The estimates of recruitment and spawning output provided here should be the 'best estimates' of these quantities.

23) "Number of years with pre-specified catches": In many cases, the first year in which the harvest strategy will be applied, y_{start}, is several years beyond the last year of the assessment, y_{init} (y^0_{init}). Catches for the years between the last year of the assessment and the first year of the rebuilding period should either be known or assumed equal to the ACL (for the current year). Enter here the number of years between the last year of the assessment and the first year in which the harvest strategy will be applied.

24) "Catches for years with pre-specified catches": Enter, for each year between the last year of the assessment and the first year of the rebuilding program, the observed catch (the catch for the current year will not be known and should be assumed equal to the ACL). The split of the fishing mortality between fleets used when removing these catches is specified at input 47) below. Note that the years for which catches are pre-specified cannot overlap with the first year for which a catch is specified at input 48) if option 4 is used at input 48).
25) "Number of recruitments to override": For some rebuilding analyses, it may be desirable to pre-specify the strengths of some of the recruitments beyond year y_{init}^0 (because of the known impact of El Nino, for example). Enter here, the number of future recruitments that will be pre-specified.
26) "Process for overriding": Enter, for each year for which recruitments are to be overridden, the year, a code which determines whether the recruitment concerned should be specified in absolute terms (1) or whether the method selected at input 12) should be used to generate the recruitment concerned (0), and a value code. How to specify the value code depends on whether 0 or 1 are selected as the second input. If recruitment is to be specified in absolute terms, the absolute level of recruitment should be entered as the value code whereas if 0 was entered at the second input, a "generation code" must be entered. The current "generation codes" are: "-1" – replace the recruitment by its expected value, "0" – generate it as usual (this option is helpful if a recruitment for a year well into the future is to be pre-specified, but this is not the case for many of the years between year y_{init}^0 and that year), and a positive number, *x*. The recruitment for the last case is then taken to be that for the historical year specified (i.e. *x*=1999 implies that the recruitment concerned should be generated based on that for the recruitment for 1999). Using this option for years before y_{init} allows the user to specify that the recruitments between y_{init}^0 and y_{init} should be set to actual recruitments rather than being generated (as is required by the PFMC for groundfish rebuilding analyses; SSC 2008, 2012). For example, if y_{init}^0 is 2000 and y_{init} is 2005, the input at this input should be:

```
2001  1 2001
2002  1 2002
2003  1 2003
2004  1 2004
2005  1 2005
```

27) "Which probability to produce detailed outputs for": Enter "1" to produce detailed results for the first rebuilding policy, "2" for the second, etc. Note that detailed results can be produced for a user-specified harvest strategy by setting this input to the code for the user-specified harvest strategy (see inputs 47 and 48) below).
28) "Steepness, sigma-R and auto-correlation": Enter the 'best estimate' of the steepness of the stock-recruitment relationship (defined as the fraction of virgin recruitment to be expected at 20% of B_0), that of the coefficient of variation of future recruitment, and that of the extent of temporal auto-correlation in the residuals about the stock-

recruitment relationship. The values entered here are only used if "3" or "4" were entered at input 12).

29) "Target SPR rate": This line lists the target spawning output-per-recruit (used to compute F_{targ}). Enter the F_{MSY} proxy spawning output-per-recruit here (this is 0.5 for rockfish).

30) "Discount rate": Enter the value for the discount rate, δ, to be used when reporting cumulative catches (see Equation 13b).

31) "Truncate the series when 0.4B0 is reached": Enter "1" here if the graphs showing time-trajectories of spawning output, catch, recruitment, fishing mortality, exploitable biomass, and cumulative (discounted) catch are to be truncated once the probability of being above $0.4B_0$ exceeds 0.5.

32) "Set F to FMSY once 0.4B0 is reached". Enter "1" to over-ride the policy of constant fishery mortality by setting the fishing mortality equal to F_{targ} once the spawning output exceeds $0.4B_0$ (see Equation 7 of the technical description). Note that under this option the fishing mortality is based on F_{ref} until the spawning output again recovers to $0.4B_0$ if the spawning output drops below $0.4B_0$ after it has recovered to this level. Enter "2" to use the X-Y rule (see Equation 8 of the technical description) to set the fishing mortality once the spawning output first reaches $0.4B_0$. Note that under this option F_{ref} is ignored once the spawning output recovers to $0.4B_0$.

33) "Maximum possible F for projections". This option specifies the maximum fishing mortality rate during the rebuilding period. Setting it to a negative number leads to the maximum fishing mortality rate during the projection period being set equal to the maximum value of F_{MSY} over all the input parameter vectors including the inputs corresponding to the 'best estimates'. It is strongly recommended that -1 be entered at this input because overfishing would occur if the fishing mortality corresponding to recovery and hence that used to set the ACL exceeded F_{MSY}. The software outputs warnings if any of the calculated constant fishing mortalities exceed F_{MSY} or if the ACL for year y_{start} exceeds the ACL for year y_{start} corresponding to F_{MSY} (the OFL for year y_{start}). Note that one can specify that the annual catch cannot exceed the annual ABC (see inputs 37 and 38).

34) "Definition of recovery": Enter "1" to use the first option for defining recovery and "2" for the second option (see Section 1.3).

35) "Projection type (1, 2, 3 , 4, 11 or 12)". The options for this input are interpreted as follows:

   a. "1" to base the rebuilding analysis on a set of probabilities of recovery by T_{max} of 0.5, 0.6, 0.7, 0.8 and 0.9;
   b. "2" to base the rebuilding analysis on a 50% probability of recovery by a range of years between T_{min} to T_{max} (these years would correspond to different choices for T_{target});
   c. "3" to conduct a "sustainability analysis" (i.e. to find the harvest strategies that have a 0.5, 0.6, 0.7, 0.8 and 0.9 probability of the spawning output after 100 years being equal to or larger than the current spawning output)
   d. "4" to base the rebuilding analysis on a 50% probability of recovery by a pre-specified set of years (this option generalizes option "2") (see input 50 for how to pre-specify the years);

e. "11" to base the rebuilding analysis on setting the spawning potential ratio equal to a pre-specified set of values (see input 50 for how to pre-specify the SPRs); or
f. "12" to base the rebuilding analysis on the SPR rates corresponding to a pre-specified set of catches for year y_{start} (see input 50 for how to pre-specify the catches).

36) "Definition of the '40-10' rule". Enter the upper and lower percentages if a control rule other than the 40-10 rule is to be applied (see Equation 8 of the technical description). The default options of "10 40" should not be changed unless a rule other than 40-10 is to be used to compute ACLs.
37) "Sigma Assessment Error". Enter the value for the "sigma" which will be used when calculating the buffer between OFL and the ABC.
38) "Pstar" Enter the value for P* which will be used when calculating the buffer between OFL and the ABC.
39) "Constrain catches by the ABC (1=Yes;2=No)". Select "1" at this option to impose the constraint that the ACL cannot exceed the ABC. This option should be set "2" if there is implementation error.
40) "Implementation error (0=No;1=Lognormal;2=Uniform)". Select how implementation error should be modeled. In general, implementation error should only be included in a rebuilding analysis once a set of target catches has been selected.
41) "Parameters of Implementation Error". Two values need to be entered. How they are interpreted depends on what was specified at the previous input. The two numbers are the bias and CV for log-normal implementation error and the upper and lower proportions between which the catch will vary for uniform implementation error.
42) "Calculate coefficients of variation". Enter "1" to quantify the Monte Carlo uncertainty associated with the ACLs for the first projection year by repeating the calculations for a variety of random number seeds.
43) "Number of replicates to use". Enter the number of times the calculations should be repeated to quantify the extent of Monte Carlo uncertainty (at least 10 is recommended). The value entered here is ignored unless "1" was entered at input 39).
44) "First random number seed". Enter a number between –1 and –99999.
45) "File with multiple parameter values". Enter the name of the file that contains the information on the alternative sets of model parameters. The file name length cannot exceed 20 characters. There should be no spaces after the file name as these spaces would count towards the 20 characters. The organization of the file for each alternative parameter vector is:
    a. Blank line.
    b. Fecundity-at-age
    c. Weight-at-age and selectivity-at-age (ordered by sex and fleet).
    d. Natural mortality and numbers-at-age for year y_{init} (females then males).
    e. Numbers-at-age for year y^0_{init} (females then males).
    f. Blank line.
    g. Annual recruitment.
    h. Annual spawning output.

i. Steepness, σ_R, and the extent of temporal correlation among the residuals about the stock-recruitment relationship (enter "0.5 0.5 0.5" if the stock-recruitment relationship was not estimated as part of the analysis).

46) "User specified projection (1=Yes); Output replaced (1->9)". Enter "1" as the first input on this line to indicate that you wish to replace one of the nine default harvest strategies by a user-defined harvest strategy. Next, enter a number between 1 and 9. The results for the user-defined harvest strategy will replace those for the default harvest strategy indicated by the number chosen (e.g. default harvest strategy 1 is a probability of recovery by $T_{\max}$ of 0.5 and default harvest strategy 8 is the 40-10 rule). If this number is the same as that entered at input 27), the full set of plots is produced for the user-defined harvest strategy.

47) "Catches and Fs". The input at this step is used to specify the user-defined harvest strategy. Each line should contain three values ("year", "type of management", and "value"). The first year must be the year for which an ACL is needed (i.e. year $y_{\rm start}$) and the year on the last line must be –1. The input is interpreted as follows: "1" for "type of management" indicates that the "value" is a fishing mortality, "2" indicates that the "value" is a catch, "3" indicates that the "value" is a spawning output-per-recruit, and "4" indicates that the fishing mortality (or spawning output-per-recruit) should be set to that for the previous year. Option "4" is used, for example, if the fishing mortality for future years is to be set to that corresponding to the catch in the first year of the projection period. For example, to set the catch for 2007 to 150t and then to project forward with the fishing mortality (or spawning output-per-recruit) equal to that for 2007, the input needs to be:

```
2007  2   150
2008  4   999
-1    -1   -1
```

If the "type of management" is the same for adjacent lines, the "value" for any intermediate years is obtained by linear interpolation. If, on the other hand, the "type of management" differs between two adjacent lines, the "value" for any intermediate year is set to that for the first of the two lines. The "value" and "type of management" for all years after the second last year (the last year is always –1) are set to those on the second last line of input.

48) "# Fixed catch project (1=Yes)": The values entered at this option allow the user to conduct projections for a pre-specified series of future catches (and hence conduct a decision analysis). The first value should be set to a number larger than 0 if a catch projection is to be conducted (the number determines how many sequences of pre-specified catches form the basis for projections). The second set of inputs on this line indicates which default harvest strategies should be replaced in the output and the third set of inputs indicates the basis for each of the catch projection. Setting one of values for this last input to a number larger than 0 (1-9) will lead to the catch projection being based on the median catch series for the harvest strategy concerned and a 0 (or less) will result in projections being based on input in the file "Catch.Inp". The catches used when using this option are always stored in the file "Catch.Use".

For example, "2 3 4 6 -1" at this input would mean that there are two constant catch projections, that the results of the projections should replace the 3rd and 4th default strategies and the projections should be based on the 6th strategy and input from "Catch.Imp".

48a) "# Special catch options": Enter "1" (to use this option), E_{MSY} (in units of 1+ biomass), distribution, a buffer, a fixed catch, and the option to replace. The removal in a year is given by $E_{MSY}\, B_y^{1+}$ distribution x buffer+fixed_catch .

48b) "B1Target": Enter the target biomass in units of 1+ biomass.

49) "# Split of Fs": The input at this step is used to specify the split of fishing mortality among the various fleets (i.e. η_y^f). Each line should contain a year and the relative fishing mortality for each fleet (these need not add to 1 – the program will ensure this). The first year must be y_{init}, and the year on the last line must be –1. If the years for adjacent lines are not sequential, fishing mortality splits for the intermediate years will be calculated by means of linear interpolation.

50) "# Five pre-specified inputs": The interpretation of this input depends on what was selected at input 35). For example, if "4" was entered at input 35), the five values are taken to be years for which the probability of recovery should be 0.5, if "11" was entered at input 35), the five values are interpreted as SPR values, and if "12" was entered at input 35), the five values are interpreted as catches during year y_{start} .

51) "# Years for which a probability of recovery is needed": The probability of recovery by these eight years will be included in the final summary table for each harvest strategy. Note that choosing years beyond $T_{\max}$ is not recommended and could lead to program crashes or nonsensical results.

52) "Time varying weight-at-age (1=Yes; 0=No)": Enter "1" to allow fecundity-at-age and weight-at-age to change over time. If this option is selected, the weights- and fecundities-at-age used for the historical period are specified by the user (see input 53). The future weights- and fecundities-at-age are then set to an average of past weights- and fecundities-at-age where the average is taken over the last y+1 years, i.e. the weights-at-age for the first projection year are set to the average of the weights-at-age for years y_{init} and $y_{\text{init-1}}$. The weights-at-age and fecundities-at-age used when computing B_0 and the proxy for F_{MSY} are the averages over the entire historical period. If there are multiple starting values, the fecundities and weights-at-age in the file specified at input 45) are scaled by the ratio of the averages computed from the input file specified at input 53) to the values for the last year in this input file.

53) "# File with time-series of weight-at-age data": Enter the name of the file that contains the historical fecundity-at-age and weight-at-age information. The format of the file must be two blank (header) lines followed by lines for each year of the historical period (i.e. for the number of years entered at input 21) of fecundity-at-age. The first entry on each line is ignored – this can be set to the year concerned. The data on fecundity-at-age is followed by weight-at-age in the same format (two blank lines, one line for each year of the historical period) sorted by fleet and sex (i.e. fleet 1, sex 1, fleet 1 sex 2, fleet 2 sex 1,….)

54) "# Use bisection (0) or linear interpolation (1)": Select 1 to use linear interpolation rather than bisection when calculating the fishing mortalities / spawning outputs-per-recruit. In principle, use of linear interpolation should lead to reduced computational

requirements, but the results will not be identical to those obtained using the bisection method (because of the effects of rounding). Version 2.8a and earlier versions of the software are based on the application of the bisection method.

55) "# Target Depletion": Enter the depletion that defines the target for the recovery strategy, γ. The default for this depletion is 0.4 as this is the proxy for B_{MSY} for most PFMC-managed species.

3. SUMMARY.XLS

The summary tables and plots are produced using the spreadsheet SUMMARY.XLS. The process for producing these tables and plots is to use the spreadsheet SUMMARY.XLS to load the CSV file produced by REBUILD.EXE (by default this file is RES.CSV) into Excel. The macro "clear output" is used first. It takes the CSV file whose name is given in cell B4 from the directory given in cell B3 (if no input is provided, the file is RES.CSV in the current directory). The "clear output" macro clears the plots, deletes any existing tables, and copies the data from the CSV file into the sheet "Data" of spreadsheet "SUMMARY.XLS". The CSV file is then closed unless the user wishes to save it under a new name. It is advised that the RES.CSV file be renamed to something meaningful to prevent output files getting confused. The macro "Basic graphs" is then run to produce the summary graphs and tables based on the information in the CSV file.

3.1. SUMMARY TABLES

The summary tables are located in the sheets "Main", "OYs", "Traject", "Prob Recovery", "Council Table", and "Monte Carlo":

- Cells B7:B16 of sheet "Main" summarize the specifications related to the number of simulations, the oldest age, the method used to generate future recruitment, whether the projections are based on constant fishing mortality or on constant catch, the assumed discount rate, the option used to define "recovery", the number of fishing fleets, the policy to apply once the spawning output recovers to $0.4B_0$, whether the calculations are based on the 'best estimates' for the vector of model parameters or a set of replicate parameter vectors, and whether there is implementation error. The three options for the policy to apply once the spawning output recovers to γB_0 are: (a) to continue to base management on the fishing mortality during the recovery period, $F_{\rm ref}$; (b) to set F to F_{MSY} when the spawning output exceeds γB_0 and set it to $F_{\rm ref}$ if the spawning output drops below γB_0; and (c) to use the 40-10 rule.
- Cells B19:B32 of sheet "Main" list the values for $F_{\rm targ}$, the ratio of the spawning output-per-recruit at $F = F_{\rm targ}$ to the virgin spawning-output-per-recruit, the virgin spawning output-per-recruit, the minimum possible rebuild time, $T_{\rm min}$, the estimated generation time (T_G - see Equation 11 of the technical description), the maximum allowable rebuild time ($T_{\rm max}$ - see Equation 9 of the technical description), the rebuild time on which the analyses are based (which may differ from $T_{\rm max}$ - see input 15) above), the year in which rebuilding is to occur, B_0, the target for rebuilding (γB_0), the spawning output at the start of year $y_{\rm init}$, the

spawning output at the start of year y_{decl}, the probability that the spawning output at the start of year y_{decl} was less than the target level of γB_0, and the probability that the spawning output at the start of year y_{decl} was less than the overfished level of $0.25B_0$.

- Cells B34:B42 summarize the basis on which T_{min} and T_{max} were calculated.
- Columns B and C of sheet "Main" starting at row 64 list the 'best estimates' for the historical time sequence of recruitments. The values highlighted in yellow form the basis for calculating the virgin recruitment.
- Columns K onwards of sheet "Main" list the 'best estimates' for fecundity-at-age, natural mortality-at-age, selectivity-at-age, weight-at-age, and numbers-at-age at the start of years y_{init} and y^0_{init}. These values are taken from the input file supplied to REBUILD.EXE (see inputs 16-19 above).
- Cells B45:J61 of sheet "Main" summarize the results for each of the nine harvest strategies. The results presented for each harvest strategy are:
    - the constant level of fishing mortality, F_{ref}, (for rebuilding analyses based on constant fishing mortality);
    - the spawning output-per-recruit on which the rebuilding analysis is based;
    - the catch during year y_{start};
    - the probability of recovery by T_{max} (expressed as a percentage);
    - the probability of recovery by a pre-specified year (expressed as a percentage);
    - the median number of years since y_{start} until there is a 0.5 probability that the spawning output exceeds γB_0;
    - the probability (expressed as a percentage) that once the population recovers to γB_0 it subsequently drops below $0.25B_0$ (the overfished level) before T_{max};
    - the year in which there is a 0.5 probability that the spawning output exceeds γB_0 – when the number of simulations is small, this year may be before year T_{max} even when the probability of recovery is 0.5;
    - the probability (expressed as a percentage) that the spawning output will be equal to or larger than the current spawning output after 100 and 200 years;
    - the probability (expressed as a percentage) that the spawning output drops below $0.01B_0$ sometime over the next 100 and 200 years; and
    - the median and 90% intervals for the ratio of the spawning output to γB_0 in year T_{max}. Note that the median of this ratio will not necessary exceed 1 for some of the strategies even though the probability of recovery is larger than 0.5 if the 2nd definition of recovery is selected (see input 34 above).
    - The probability that the spawning output drops below that at the start of year y_{decl} at least once during the projection period.
    - The probability that the spawning output drops below that at the start of year y_{start} at least once during the projection period.

The default harvest strategies for columns G-J are (a) a probability of recovery of 0.5 by $T_{\min} + 0.5(T_{\min} + T_{\max})$, (b) the zero-catch strategy, (c) the X-Y rule (note that the F_{MSY} proxy used for the X-Y rule is F_{targ} - see input 29), and (d) the ABC control rule. Note that the year in which there is 0.5 probability that the spawning output exceeds γB_0 will not always equal $T_{\min}$ when F=0 if some catches have occurred since y_{decl}. This is because $T_{\min}$ is calculated assuming that F=0 from year y_{decl} whereas the F=0 strategy in column H is based on setting F=0 after year y_{start} (i.e. the results for F=0 are based on projecting from y_{init} to y_{start} based on the actual catches for those years whereas $T_{\min}$ is calculated by projecting y_{decl} to y_{start} under zero catches). Note that if a user-specified harvest strategy is used or projections are conducted for pre-specified sequences of catches, the results for these harvest strategies replace those for some of the nine strategies. The column containing the results for the user-defined harvest strategy has "User specified" in rows 49 and 50, while the results of projections based on a pre-specified set of catches are labeled "Catch Proj".

- The sheet "ACLs" lists the medians of the distributions for the time-trajectories of ACL for the first 10 years of the projection period for each of the harvest strategies. If there are more than two fleets, the ACLs by fleet for the first 10 years of the projection period are also provided.
- The sheet "Traject" lists the medians of the distributions for the time-trajectories of ACL, the ABC catch, spawning output, spawning output relative to B_0, and the spawning potential ratio for each of the nine harvest strategies. The ABC catch for year y in these tables is the ABC (i.e. the catch corresponding to the F_{MSY} proxy multiplied by the buffer between the OFL and the ABC) computed given that all previous catches have been taken using the harvest strategy for which results are being reported.
- The sheet "Prob Recovery" lists the probability of recovery to γB_0 for each year of the projection period for each of the nine harvest strategies.
- The sheet "Council Table" lists the values for the key parameters required in rebuilding analyses submitted to the Pacific Fishery Management Council (see SSC (2008) for details) for each of the nine rebuilding analyses.
- Row 4 of the sheet "MonteCarlo" lists the coefficients of variance (expressed as percentages) for the minimum possible rebuild time, $T_{\min}$, the maximum allowable rebuild period, $T_{\max}$, and the ACLs for the first projection year corresponding to probabilities of recovery by year $T_{\max}$ of 50%, 60%, 70% and 80%. Row 3 of this sheet summarizes the mean values (across replicates based on different random number seeds) for these six quantities. The raw information used when calculating the values in rows 3 and 4 is given starting in row 6.

3.2 SUMMARY PLOTS

The summary plots are located in the sheet "Plots".

- The top left plot shows net spawning output (based on the 'best estimates' of natural mortality-at-age) against age.

- The second plot on the first row of plots shows the distribution for B_0.
- The third and fourth plots on the top line of plots show the 'best estimates' of the recruitments and recruits-per-spawning output. If no recruitments are selected at input 22) of REBUILD.DAT, the plot for recruitment is dropped. Similarly if no recruits per spawning output are specified, the recruits per spawning output plot is not displayed.
- The fifth plot on the top line of plots is historical recruitment ('best estimates') plotted against the corresponding spawning output with the specified stock-recruitment relationship (see input 28) above) imposed. This plot is only produced if the rebuilding analysis is based on a stock-recruitment relationship.
- The last plot on the top line of plots is historical recruitment ('best estimates') plotted against the corresponding spawning output with the relationships between recruitment and spawning output based on Fs of 0, the pre-specified F_{MSY}, and two estimates of F_{rep} (lines placed through the median and mean of the pre-specified recruits per spawning output data). This plot is only produced if the rebuilding analysis is based on selecting recruits per spawning output at random from a pre-specified set of recruits per spawning output.
- The leftmost plot on the second row of plots shows the distribution of the time that it takes to recover to γB_0 if F=0. The "minimum possible rebuild time", T_{min}, is the median of this distribution.
- The next three plots on the second row of plots show the probability of being above the target level, the median catch and the median of the ratio of spawning output to γB_0 as a function of time for nine harvest strategies (the nine harvest strategies for which results are provided in cells B45:J59; the exact specifications for those strategies depend on the values entered at inputs 35) and 45).
- The rightmost plot on the second row of plots shows the distribution on which the value of T_{max} is based; T_{max}, is the median of this distribution.
- The plots on the third and fourth lines show the 5^{th}, 25^{th}, 50^{th} (indicated in red), 75^{th} and 95^{th} percentiles of the distributions for the time-trajectories of spawning output (expressed relative to the target level), catch, recruitment, fishing mortality, exploitable biomass, and cumulative catch. The harvest strategy for these plots is the strategy highlighted in cells B45:J59 of the sheet "Main". If "1" was entered at input 32), the trajectories are truncated once the spawning output reaches γB_0.
- The third plot on the fourth line shows the ratio of the spawning output to the target level for the first five simulations for the harvest strategy highlighted in cells B45:J59. The horizontal line indicates the target level.
- The fourth plot on the fourth line shows the distribution of the time for each simulation to first reach the target level for the harvest strategy highlighted in cells B45:J59, along with the probability for each year that the spawning output exceeds the target level in the year concerned (yellow line) and the probability for each year that the spawning output reached (but may have again dropped below) the target level (pink line). The difference between the pink and yellow lines indicates the fraction of simulations in which the spawning output drops below

the target level once it has been reached. The black line indicates T_{max} and the probability associated with the selected harvest strategy.

4. USAGE NOTES AND WARNINGS

- If you want to know where in the sheet "Data" the data that were used to construct a particular plot are located, right click on the plot and go to the "Data sources" tab.
- The values in row 48 of the sheet "Main" will not be exactly 50, 60, 70, 80 and 90 even when the rebuilding analyses are based on fixing these values because of the use of a numerical procedure to find the reference level of fishing mortality (and catch).
- To pre-specify B_0 (and hence $0.4B_0$), add a line to the historical data at input 22) listing the virgin recruitment (B_0 divided by the virgin spawning-output-per-recruit), B_0 and indicating that this line (alone) will be used to define B_0.

5. EXAMPLE INPUT FILES

Three example input files are included with the software.

1) Rebuild.EX1. This input file conducts a rebuilding analysis for Pacific Ocean perch in which parameter uncertainty is ignored and the projections are consequently based on the maximum posterior density (MPD) estimates of the parameters. Future recruitment is generated by selecting randomly from past recruitments and B_0 is determined from an estimate of pre-fishery recruitment from the stock assessment.
2) Rebuild.EX2. This input file is identical to Rebuild.EX1 except that the projections take account of parameter uncertainty in addition to uncertainty about future recruitment. This analysis is based on 5 projections for each of 1,000 parameter vectors. The results for this example are based on a user-specified harvest strategy in which the catch from 2010 is based on the spawning potential ratio corresponding to a 2009 catch of 275t.
3) Rebuild.EX3. This input file conducts a rebuilding analysis for widow rockfish (case 8 of Table 4 of He *et al.* 2003). The rebuilding analysis is based on a sex-specific model, generates future recruitment by resampling recruits-per-spawner ratios, defines B_0 using the average recruitment over the first 15 years of the assessment period, and pre-specifies the recruitments for the first three years of the projection period.

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Appendix A : The Modifications made to the Rebuilding Analysis Software

- 1.000002: Minor typographical errors in the documentation corrected.
- 1.000003:
  i. Additions:
    1. new diagnostic plots (probability of recovery in the maximum allowable rebuilding period versus a 50% probablity in some shorter period; time-trajectory of the distribution of the cumulative (discounted) catch);
    2. the ability to examine an additional "transitional" policy;
    3. the ability to select one of two definitions for "recovery";
    4. the ability to pre-specify the maximum allowable rebuilding period; and
    5. the ability to change from the fishing mortality defined in the rebuilding strategy to an F_{MSY} proxy once the resource recovers to $0.4B_0$.

  ii. Corrections: removed an error in the calculation of the maximum allowable rebuilding period.

  iii. Minor modifications: added the ability to omit the printing of results once $0.4B_0$ has been reached.
- 1.2:
  i. Additions:
    1. Added a plot showing the expected recruitment as a function of spawning output for F_{rep}, F=0, and F=F_{MSY}, along with the recruitment and spawning output data.
    2. Included the year when the population was declared overfished into the calculation of the maximum possible rebuild period.

  ii. Minor modifications:
    1. Added a warning if the predicted first-year spawning output differs from the pre-specified first-year spawning output.
    2. Added additional summary statistics (F_{MSY}).
- 1.3 (March 2002):
    1. Included specification of the random number seed as an input to allow sensitivity to this seed to be examined.
- 1.4 (April 2002):
    1. Improved the efficiency of the search for the "target" fishing mortalities.
    2. Added the ability to automatically quantify the Monte Carlo uncertainty associated with the calculation of the OYs for the first year of the projection period.
- 1.5 (May 2002):
    1. Modified the definition of T_{max} to take account of the time from being declared overfished until the first year of the projection.
    2. Added three additional graphical summaries.
- 2.0 (June 2002; Major update):
    1. Added additional error messages to capture mistakes in the input file related to the years to which the inputs relate.
    2. Modified the approach to compute T_{min} based on advice regarding its definition. The zero catches now commence immediately after year y_{decl}.

3. Added the ability to calculate the probability that a "recovered" stock drops below the overfished threshold of $0.25B_0$ due to recruitment variability.
4. Corrected an error that occurred if the population could not recover in the absence of catches within 500 years.
5. Automated the process of loading the CSV file.
6. Added the option to use the 40-10 rule once rebuilding has first occurred.

- 2.1 (July 2002)
  1. Added an error message if recovery with 50% probability occurs after more than 500 years under zero catch.
  2. Corrected the implementation of the 40-10 rule so that catch rather than the fishing mortality is modified if the population is below $0.4B_0$.
  3. Added the actual years corresponding to T_{min} to the results in cells B45:G49 in addition to the years relative to y_{start} and y_{decl}.
  4. Included the ability to display rebuilding strategies based on there being a 50% probability of recovery to $0.4B_0$ for a range of years rather than on there being a range of probabilities of recovery by T_{max}.
  5. Included the ability for the user to specify a harvest strategy.
- 2.2 (July 2002)
  1. Added the ability to have more than one fleet.
- 2.3 (October 2002)
  1. Added the ability to allow for uncertainty in the initial numbers-at-age vector and in the values for natural mortality- and weight-at-age.
- 2.4 (November 2002)
  1. Modified the EXCEL macros to reduce the size of the Visual Basic code.
  2. Included temporal auto-correlation in the residuals about the stock-recruitment relationship.
  3. Added the ability to allow for uncertainty in the parameters of the stock-recruitment relationship.
- 2.5 (April 2003)
  1. Modified the approach used to pre-specify recruitments so that an absolute value can be entered.
- 2.6 (April 2003)
  1. Added the probability of the spawning output being at or above the current spawning output after 100 and 200 years, and the probability of the spawning output dropping below 1% of B_0 sometime over the next 100 or 200 years to the output.
  2. Added the ability to select F-levels so that the probability that the spawning output is at or above the current spawning output equals pre-specified values (50, 60, 70 and 80%).
- 2.7 (July 2003)
  1. Added the results for an additional three rebuilding strategies (P_{max}=0.9; T_{target}=T_{mid}; and F=F_{ABC}).
  2. Added the time-trajectories of OY, the ABC catch, spawning output and spawning output relative to the target spawning output to SUMMARY.XLS. These trajectories are needed when reporting the results of rebuilding analyses.

3. Extended the user-specified rebuilding option so that the user can conduct rebuilding analyses based on a pre-specified value for P_{max}, a pre-specified value for T_{target} or a pre-specified probability that the population exceeds its current level in 100 years.
4. Modifed the risk-reward plots to include information on $T_{mid} = (T_{max}+T_{min})/2$ and T_{max}.

- 2.7b (August 2003)
  1. Corrected some minor output errors.
- 2.7c (September 2003)
  1. Added an error message warning the user if the OY exceeds the ABC OY.
- 2.7d (September 2003)
  1. Generalized the 40-10 rule to allow for more general rules.
- 2.7e (January 2004)
  1. Added the ability to allow weight-at-age and fecundity-at-age to vary over time.
- 2.8 (January 2005)
  1. Added the ability to input and output spawning output -per-recruit rather than fishing mortality.
  2. Output a distribution for T_{max}.
- 2.8a (April 2005)
  1. Added the median and 95%iles for the ratio of the spawning output to the target spawning output for each rebuilding strategy.
- 2.9 (December 2005)
  1. Added the ability to calculate the critical fishing mortalities and spawning biomass-per-recruits using a linear interpolation rather than bisection.
  2. Extended the multi-parameter version of the program so that fecundity can differ among parameter vectors.
  3. Changed the order of the input when there are multiple parameter vectors so that the order in which these data are entered is the same as that when there is only a single parameter vector.
  4. Added the ability to have a target depletion other than 0.4.
  5. Added a report of catch projections (by fleet) for the first 10 years of the projection period.
- 2.10 (August 2006)
  1. Modified the 40-10 rule to be consistent with SS2.
  2. Added the spawning potential ratio to the output included in the sheets "data" and "traject".
  3. Expanded on the description for option 4 under "Catches and Fs".
  4. Modified the input of recruitment and spawning biomass in REBUILD.DAT to better match SS2.
  5. Incorporated the possibility of log-normal implementation error.
- 2.10a (December 2006)
  1. Minor changed to make the input files clearer to follow.
- 2.11 (September 2007)
  1. Added the ability to pre-specify a range of T_{target}s (projection type 4)

2. Added the ability to output the probability of recovery by any pre-specified year

- 2.11a (September 2007)
  1. Modified how the linear interpolation method works when the upper bound for *F* equals the maximum possible
- 3.1 (May 2008)
  1. Replaced all fixed length arrays with dynamic arrays – allows more flexibility in terms of the number of fleets, years, and ages.
  2. Added the ability to project based on a range of SPR rates and catches in the first year of the projection period.
  3. Modified the code so that the indices are based on years rather than offsets – improves the ability to validate the code and create output.
  4. Added two new summary tables based on Council needs.
  5. Removed two (unused) transition policy options.
  6. Add the ability to conduct projections based on a pre-specified series of catches.
- 3.11 (June 2008)
  1. Extended the ability to project based on pre-specified catches to automatically compute a decision table.
  2. Modified headers and implemented minor clean up.
- 3.12 (May 2009)
  1. Added input echo to assist with checking.
- 3.12a (September 2009)
  1. Fixed an output error with input echoing.
- 3.12b (January 2010)
  1. Rounded years in the output viewer up automatically.
  2. Output specified for use in R
- 3.12c (December 2011)
  1. Constrained catches by ABCs
- 3.12d (April 2012)
  1. Revised how Implementation Error is modeled
  2. Updated how catches are constrained by ABCs
  3. Updated R code for summarizing outputs.
- 3.12e (June 2012)
  1. Updated the output of detailed results
- 3.12f (July 2020)
  1. Added in a sardine ABC-like control rule
  2. Added in reporting of time to recovery to a target 1+ biomass