

**INTERNATIONAL COMMISSION FOR THE CONSERVATION  
OF ATLANTIC TUNAS**

**COMMISSION INTERNATIONALE POUR LA CONSERVATION  
DES THONIDES DE L'ATLANTIQUE**

**COMISION INTERNACIONAL PARA LA CONSERVACION  
DEL ATUN ATLANTICO**



**ASSESSMENT PROGRAM DOCUMENTATION**

**Program:** **PRO-2BOX (ver. 2.01)**

Projects the future abundance and mortality of animal populations from historical levels assuming several possible relationships between recruitment and spawning stock biomass and a prescribed vector of future vulnerability at age. Accommodates two intermixing populations, sex-specific analyses and multiple fleets. Includes equilibrium yield per recruit and spawner per recruit computations..

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**NOTE:** As part of its efforts to carry out Quality Management, ICCAT's Standing Committee on Research and Statistics is developing a catalog of stock assessment applications. The purpose of the catalog is not to evaluate the relative merits of various assessment methods,

but rather whether the software implementing the method works as intended and is adequately documented.

## 1. PROGRAM NAME

PRO-2BOX

## 2. VERSION (DATE)

Version 2.01, dated October, 2002

## 3. LANGUAGE

Fortran 90

## 4. PROGRAMMER / CONTACT PERSON

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## 5. DISTRIBUTION LIMITATIONS

Only executable code can routinely be distributed, along with the manual and example files. Source code is available from the author upon written request and with agreement to certain restrictions.

## 6. COMPILER NEEDS / STAND-ALONE

Does not require software other than an operating system with DOS-emulating capabilities such as Windows (Windows 9x, 2000 or NT). Users must be able to print and edit ASCII files.

## 7. PURPOSE

To project the future abundance and mortality of animal populations from historical levels assuming several possible relationships between recruitment and spawning stock biomass and a prescribed vector of future vulnerability at age. Accommodates two intermixing populations, sex-specific analyses and multiple fleets. Includes equilibrium yield per recruit and spawner per recruit computations.

## 8. DESCRIPTION

**NOTE: Version 2.01 replaces Version 2.0. See Section 18 for a description of changes.**

The program includes two types of intermixing: diffusion and overlap (Table 1). The former assumes a fraction  $\tilde{T}_{jk}$  of the population in management zone  $j$  transfers to zone  $k$  whereas the latter assumes a fraction  $T_{sk}$  of stock  $s$  transfers to zone  $k$ . Both models reduce to single-stock VPA's when the  $T$  (or  $\tilde{T}$ ) are set to zero. For convenience  $T$  and  $\tilde{T}$  are both referred to as transfer coefficients, but the two are not directly comparable because the diffusion model allows fish born in one zone to accumulate in the other. For example, if the transfer fractions for both stocks were both 10% (ignoring for the moment mortality), the diffusion model would calculate that 10% of the fish born in stock 1 will be living with stock 2 after one year, 18% after two years and 24.4% after three years.



**Table 1.** Overlap and diffusion model equations describing population dynamics (stock:  $s$ , age:  $a$ , year:  $y$ , zone:  $j$  or  $k$ ,  $A$ : age of plus-group,  $Y$ : most recent year in analysis).

Equations and variables	Description
$C_{kay} = \tilde{N}_{kay} \frac{F_{kay}(1 - e^{-Z_{kay}})}{Z_{kay}}$	Catch at age $a$ in year $y$ from all stocks in management zone $k$
$Z_{kay} = F_{kay} + M_{kay}$	Total mortality rate in zone $k$
$F_{kay}$	Fishing mortality rate in zone $k$
$M_{kay}$	Natural mortality rate in zone $k$
<b>Overlap model</b>	
$N_{s,a+1,y+1} = N_{say} \sum_k T_{skay} e^{-Z_{kay}}$	Number of fish from stock $s$ that are age $a+1$ at the beginning of year $y$ ( $a+1 < A$ )
$N_{s,A,y+1} = \sum_{a=A-1}^A N_{say} \sum_k T_{skay} e^{-Z_{kay}}$	Number of fish from stock $s$ that are age $A$ or older at the beginning of year $y$
$\tilde{N}_{kay} = \sum_s T_{skay} N_{say}$	Number of fish in zone $k$ that are age $a$ at the beginning of year $y$ (all stocks combined)
$T_{skay}$	Fraction of stock $s$ residing in zone $k$ at the beginning of year $y$
<b>Diffusion model</b>	
$\tilde{N}_{k,a+1,y+1} = \sum_j \tilde{N}_{jay} \tilde{T}_{jkay} e^{-Z_{kay}}$	Number of fish in zone $k$ that are age $a+1$ at the beginning of year $y$ ( $a+1 < A$ )
$\tilde{N}_{k,A,y+1} = \sum_{a=A-1}^A \sum_j \tilde{N}_{jay} \tilde{T}_{jkay} e^{-Z_{kay}}$	Number of fish in zone $k$ that are age $A$ or older at the beginning of year $y$
$\tilde{T}_{kjay}$	Fraction of population in zone $j$ that moves to zone $k$ at the beginning of year $y$

### Summary of major assumptions

See the catalog entry for VPA-2BOX.

## 9. REQUIRED INPUTS

1. Matrices of historical abundance, fishing mortality rate, total catch (by each fleet), fraction of catch discarded (by fleet) and weight for every age, year and stock/sex.
2. Vectors of natural mortality, transfer coefficients and future vulnerability modifiers by age
3. Parameters defining the spawner-recruit relationship (Two-line, Ricker or Beverton/Holt curves)
4. Time stream of future total allowable catch or fishing mortality rate limits.

## 10. PROGRAM OUTPUTS

ASCII files are written after each run containing the projected recruitment, fishing mortality rate, spawning

stock biomass, total biomass, fishable biomass, landings in weight and benchmark statistics such as the maximum sustainable yield, maximum yield per recruit and spawning potential ratio. Two separate files are written, one containing the results for each individual run and one containing the mean, median and confidence limits from all of the runs combined.

## **11. DIAGNOSTICS**

1. Warning messages for certain invalid inputs.

## **12. OTHER FEATURES**

1. Numerous options explained in the attached manual.

## **13. HISTORY OF METHOD PEER REVIEW**

The present program is based on the framework described by Shepherd (1982), Restrepo et al. (1994), ICCAT (1997), Porch and Turner (1999) and Butterworth and Geromont (1999). Various implementations have been used by several different species groups within ICCAT (bluefin tuna, albacore and swordfish).

## **14. STEPS TAKEN BY PROGRAMMER FOR VALIDATION**

The author has written several spreadsheet programs to generate simulated data sets without imposed errors. These were then analyzed by PRO-2BOX to verify that the routine performs as expected. This testing procedure has been applied to most of the options available in the program. The author has also successfully duplicated the projections made during 2000 SCRS assessment of North Atlantic albacore.

## **15. TESTS CONDUCTED BY OTHERS**

The latest version of PRO-2BOX has not yet been evaluated by others. However, A. E. Punt (U. Washington) has indicated he holds code that would be useful for cross checking some of the options available in PRO-2BOX.

## **16. NOTES BY ICCAT**

None.

## **17. SOURCES CITED**

- BUTTERWORTH, D. S., and H. F. Geromont. 1999. Some aspects of adapt vpa as applied to north atlantic bluefin tuna. *Iccat coll. Vol. Sci. Pap.* 49(2):233-241
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- RESTREPO, V. R. , porch, C. E., Turner, S. C., Scott, G. P., Rosenberg, a. A. 1994. Combination of spawner-recruit, spawning biomass-per-recruit and yield-per-recruit computations for the estimation of the long term potential for west atlantic bluefin tuna. *Iccat collect. Vol. Sci. Pap.* 42:214-222.
- SHEPHERD, J. G. 1982. A versatile new stock-recruitment relationship for fisheries, and the construction of sustainable yield curves. *J. Cons. Int. Explor. Mer* 40:67-75.

## **18. AUTHOR'S NOTES**

## **WHAT'S NEW IN VERSION 2.01?**

This update of version 2.0 includes four changes:

1. The optional penalty function used in the spawner-recruit fitting routine to keep the predicted maximum recruitment from being too much larger than the maximum observed value has been extended. It now can also constrain the predicted maximum to values near the average of a range of observed recruitments (see discussion of spawner-recruit relationship file).
2. The estimated standard error of recruitment, which is used to generate stochastic projections, can now be constrained to be above some minimum value
3. The Ricker (1954) spawner-recruit curve, formerly available only for projections, is now also available for equilibrium computations (e.g., MSY).
4. A bug was fixed in the numerical routine for determining the fishing mortality rate that will achieve a given TAC when there are multiple fleets.

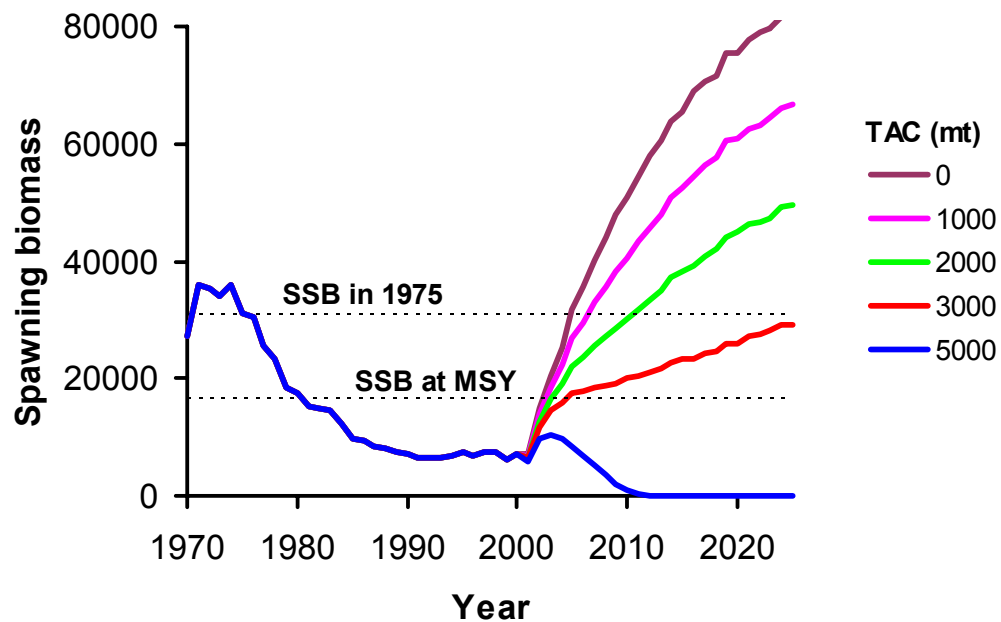
## **APPENDIX 1. ALGORITHM**

See the Users' Guide in **Appendix 2**.



# PRO-2BOX *Version 2.01*

## User's guide



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Sustainable Fisheries Division Contribution SFD-02/03-182  
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# 1. GETTING STARTED

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PRO-2BOX is a software tool developed to project the future abundance and mortality of exploited animal populations. It has been designed to accommodate all of the options available in program VPA-2BOX (Porch, 2002), including two intermixing stocks and sex-specific analyses. Other useful features include the ability to account for animals that are discarded dead and the ability to model individual fleets separately. The general theory behind the software is highlighted in Chapter 2. Specific details are reserved for Chapter 3, which covers all of the available options via a line by line discussion of the input files.

## WHAT'S NEW IN VERSION 2.01?

This update of version 2.0 includes four changes:

1. The optional penalty function used in the spawner-recruit fitting routine to keep the predicted maximum recruitment from being too much larger than the maximum observed value has been extended. It now can also constrain the predicted maximum to values near the average of a range of observed recruitments (see discussion of spawner-recruit relationship file).
2. The estimated standard error of recruitment, which is used to generate stochastic projections, can now be constrained to be above some minimum value
3. The Ricker (1954) spawner-recruit curve, formerly available only for projections, is now also available for equilibrium computations (e.g., MSY).
4. A bug was fixed in the numerical routine for determining the fishing mortality rate that will achieve a given TAC when there are multiple fleets.

## DISCLAIMER AND CONDITIONS OF USE

The manual and executable versions of PRO-2BOX can be obtained free of charge either by contacting the author<sup>1</sup> or by visiting <http://www.iccat.es/>. Copies of the executable code and manual for PRO-2BOX may be distributed without restriction, however those desiring source code should send a written request directly to the author and will be asked to abide by certain restrictions. The development of PRO-2BOX is ongoing, and the author appreciates comments regarding it, including any suspected bugs. However, no formal technical support is offered.

There is no warranty of any kind. While every effort is made to ensure the program performs

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<sup>1</sup>Address on front cover of this manual.

as described in the manual, the author and the U.S. government cannot be held responsible for any errors therein.

## SYSTEM REQUIREMENTS

- 80486, Pentium series, or compatible processor (standard PC's and clones)
- MS-DOS, IBM OS/2, or Microsoft Windows (9x, 2000, NT) operating systems<sup>2</sup>
- 1 MB of available hard disk space (30 MB for some bootstrap applications)

## NOTATIONAL CONVENTIONS

- *Italics* indicate mathematical variables or text to be replaced by the user.
- `Courier` font indicates text in a file or keystrokes.

## INSTALLING AND RUNNING PRO-2BOX

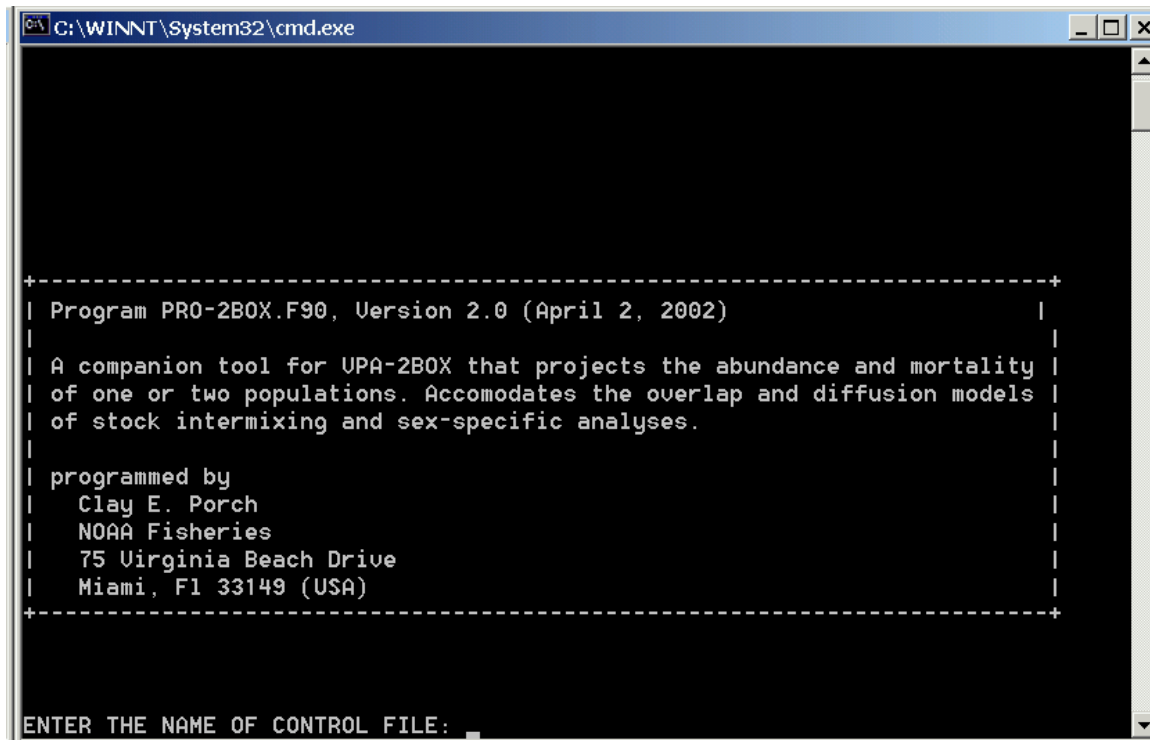
The files needed for a complete installation are normally sent as a self-extracting PKZIP file. The only steps required are:

- Copy file *PRO-ZIP.exe* to a directory on your hard drive
- Run *PRO-ZIP.exe* (or open a DOS window, move to the chosen directory, and enter *PRO-ZIP*)
- Add the chosen directory to your PATH statement as described in the documentation for your operating system and reboot your system (or place a copy of PRO-2BOX.exe in the directory where you plan to do the analyses)

The program may then be started using the Windows Run dialog, entering the name PRO-2BOX at a DOS prompt, or double clicking on the PRO-2BOX . EXE icon in Windows Explorer. The screen display will then appear as follows:

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<sup>2</sup>Reference to trade names does not imply endorsement by NOAA or the U.S. Government.



```
C:\WINNT\System32\cmd.exe

+-----+
| Program PRO-2BOX.F90, Version 2.0 (April 2, 2002) |
| A companion tool for UPA-2BOX that projects the abundance and mortality |
| of one or two populations. Accomodates the overlap and diffusion models |
| of stock intermixing and sex-specific analyses. |
| |
| programmed by |
| Clay E. Porch |
| NOAA Fisheries |
| 75 Virginia Beach Drive |
| Miami, Fl 33149 (USA) |
+-----+

ENTER THE NAME OF CONTROL FILE: 
```

The bottom line of the screen prompts the user for the name of an ASCII text file that contains the specifications needed to control PRO-2BOX. There is no graphical user interface; PRO-2BOX runs only as a console-mode program that takes all input from binary or ASCII text files (described in chapter 3). The screen is used only to enter the name of the control file and to display certain error and advisory messages. Hence, the user must be able to create and edit ASCII text files.

## 2. THEORY BEHIND PRO-2BOX

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PRO-2BOX projects the future state of the resource from estimates of its present state by making certain assumptions about fishery selectivity and the reproductive capability of the stock. The most distinctive feature of PRO-2BOX is its ability to examine two distinct groups simultaneously, making it amenable to sex-specific or two-stock analyses.

### DETERMINISTIC POPULATION DYNAMICS

The program includes two types of box-transfer models: Diffusion and overlap (see Tables 1 and 2 below). The former assumes a fraction  $T_{jk}$  of the population located in management zone  $j$  transfers to management zone  $k$  whereas the latter assumes a fraction  $\tilde{T}_{sk}$  of stock  $s$  transfers to management zone  $k$ . Both models reduce to single-stock VPA's when the transfer fractions are set to zero, otherwise  $T$  and  $\tilde{T}$  are not directly comparable inasmuch as the diffusion model allows fish born in one zone to accumulate in the other (see Porch et al, 2001; Porch, 2002).

Table 1. Overlap equations for population dynamics.

Equation	Description
$N_{s\alpha y} = R(SSF_{s, y-\alpha})$	Number of fish in the youngest age class $\alpha$ recruiting to stock $s$
$N_{s, a+1, y+1} = N_{say} \sum_k T_{skay} e^{-Z_{kay}}$	Number of fish from stock $s$ that are age $a+1$ at the beginning of year $y$ ( $a+1 < A$ )
$N_{s, A, y+1} = \sum_{a=A-1}^A N_{say} \sum_k T_{skay} e^{-Z_{kay}}$	Number of fish from stock $s$ that are age $A$ or older at the beginning of year $y$
$\tilde{N}_{kay} = \sum_s T_{skay} N_{say}$	Number of fish in zone $k$ that are age $a$ at the beginning of year $y$ (all stocks combined)
$T_{skay}$	Fraction of stock $s$ residing in zone $k$ at the beginning of year $y$
$Z_{kay} = F_{kay} + M_{kay}$	Loss rate coefficients representing the effect of fishing ( $F$ ) and natural mortality ( $M$ )
$SSF_{sy} = \sum_a P_{sa} w_{say} N_{say} e^{-Z_{kay} t_{spawn}}$	Aggregate fecundity of spawners in stock $s$ at time of spawning ( $t_{spawn}$ ) during year $y$
$P_{sa}$	Proportion of stock $s$ that is sexually mature
$w_{say}$	Weight (fecundity) of individuals from stock $s$

Table 2. Diffusion equations for population dynamics.

Equation	Description
$N_{k\alpha y} = R(SSF_{k, y-\alpha})$	Number of fish in the youngest age class $\alpha$ recruiting to zone $k$ (expressed as a function $R$ of spawning biomass $SSB$ in zone $k$ )
$\tilde{N}_{k, a+1, y+1} = \sum_j \tilde{N}_{jay} \tilde{T}_{jkay} e^{-Z_{kay}}$	Number of fish in zone $k$ that are age $a+1$ at the beginning of year $y$ ( $a+1 < A$ )
$\tilde{N}_{k, A, y+1} = \sum_{a=A-1}^A \sum_j \tilde{N}_{jay} \tilde{T}_{jkay} e^{-Z_{kay}}$	Number of fish in zone $k$ that are age $A$ or older at the beginning of year $y$
$\tilde{T}_{jkay}$	Fraction of population in zone $j$ that moves to zone $k$ at the beginning of year $y$
$Z_{kay} = F_{kay} + M_{kay}$	Loss rate coefficients representing the effect of fishing ( $F$ ) and natural mortality ( $M$ )
$SSF_{ky} = \sum_a p_{ka} w_{kay} N_{kay} e^{-Z_{kay} t_{spawn}}$	Aggregate fecundity of spawners in zone $k$ at time of spawning ( $t_{spawn}$ ) during year $y$
$p_{ka}$	Proportion of stock in zone $k$ sexually mature
$w_{kay}$	Fecundity (or weight) of individuals in zone $k$

Note that the number of fish in the youngest age class ( $\alpha$ ) is presumed to be a function  $R$  of the spawning stock fecundity  $\alpha$  years earlier (see discussion of spawner-recruit relationship file for available choices). Spawning stock fecundity is computed as the number of mature adults multiplied by some measure of their per capita fecundity. Typically this measure is weight, read from a file or computed via a growth curve, but other measures such as number of eggs produced can be used (see discussion of line 62 in the control file).

Once the relationship between recruitment and spawning biomass has been specified, the only other requirements are related to specifying the age-specific variables  $M$  and  $T$  (read from files) and the future values of  $F_{kay}$  for each age group. Program PRO-2BOX assumes that future  $F$  vectors are separable into an age-specific relative-vulnerability vector  $v$  (which implicitly includes gear selectivity, regulatory controls, and the fraction of the stock exposed to the fishery) and a year-specific apical fishing mortality rate  $\phi$  (the  $F$  on the most vulnerable age class):

$$F_{kay} = \phi_{ky} v_{ka} \quad (2.1)$$

The vulnerability vector may be specified manually or computed from historical estimates (see discussion of line 36 in the control file). The apical fishing mortality rate may be specified manually,

set to some average of the historical estimates, equated with one of several benchmarks (e.g.,  $F_{0.1}$ ,  $F_{MSY}$ ), or computed so as to achieve a prescribed total allowable catch (see discussion of quotas file). In case of the latter, it is important to allow for the possibility that some fraction of the catch may not be landed, but discarded dead. Hence, the fishing mortality rate coefficients should reflect those losses, but the computations of future landings should not. Accordingly, PRO-2BOX allows the user to discriminate between the total catch (see catch file) and the fraction that was discarded dead  $\delta$  (see discard file). Thus, the relevant equation for the landed catch biomass is

$$C_{kay} = \frac{F_{kay}(1 - \delta_{kay})}{Z_{kay}} \tilde{N}_{kay}(1 - e^{-Z_{kay}}) w_{kay} \quad . \quad (2.2)$$

## PER-RECRUIT STATISTICS

Program PRO-2BOX computes a number of the common benchmark statistics used in fisheries management, including maximum sustainable yield and spawning potential ratios. These benchmarks fundamentally depend on calculations of yield per recruit and spawn per recruit, which are explained below. The details pertaining to the particular management benchmarks produced by PRO-2BOX are discussed in the sections that follow. At present, PRO-2BOX bases all per-recruit computations on a single overall vulnerability vector and a single overall growth curve.

### Yield per recruit

#### Single stock analyses

The expected yield in weight from a given recruit under a constant apical fishing mortality rate  $\phi$  is computed as

$$\left(\frac{Y}{R}\right)_\phi = \phi \left[ \frac{v_\alpha w_\alpha (1 - S_\alpha)}{Z_\alpha} + \frac{v_{\alpha+1} w_{\alpha+1} (1 - S_{\alpha+1})}{Z_{\alpha+1}} S_\alpha + \frac{v_{\alpha+2} w_{\alpha+2} (1 - S_{\alpha+2})}{Z_{\alpha+2}} S_\alpha S_{\alpha+1} + \dots + \frac{v_{\alpha+n} w_{\alpha+n} (1 - S_{\alpha+n})}{Z_{\alpha+n}} \prod_{i=0}^{n-1} S_{\alpha+i} \right] \quad (2.3)$$

where  $\alpha$  is the age at recruitment,  $Z_a = \phi v_a + M_a$  is the instantaneous mortality rate coefficient,  $S_a$  is the probability that the recruit will survive from age  $a$  to age  $a+1$  ( $= e^{-Z_a}$ ),  $v_a$  is the relative vulnerability of age class  $a$ ,  $w_a$  is the expected weight at age in the catch and  $n$  is the potential number of age classes in the stock. Note that, if some animals are discarded dead, then the  $v_a$  terms in the numerators of equation (2.3) must be multiplied by  $(1 - \delta_a)$ .

In the case of a plus-group, where fish aged  $A$  and older are presumed to have the same relative vulnerability and natural mortality rate, the yield per recruit equation may be written as

$$\left(\frac{Y}{R}\right)_\phi = \phi \left[ \frac{v_\alpha w_\alpha (1 - \delta_\alpha) (1 - S_\alpha)}{Z_\alpha} + \sum_{a=\alpha+1}^{A-1} \frac{v_a w_a (1 - \delta_a) (1 - S_a)^{a-1}}{Z_a} \prod_{i=\alpha}^{a-1} S_i + \left( \frac{v_A \bar{w}_A (1 - \delta_A) (1 - S_A)^{A-1}}{Z_A} \prod_{i=\alpha}^{A-1} S_i \right) \sum_{t=0}^{n-1} S_A^t \right] \quad (2.4a)$$



Typically,  $n$  is chosen to be some arbitrary number large enough such that subsequent terms are negligible. However, the summation over  $t$  on the far right of equation (2.4a) is a geometric series with solution  $(1-S_A^n)/(1-S_A)$ , which in the limit as  $n$  goes to infinity is simply  $1/(1-S_A)$ . Hence,

$$\left(\frac{Y}{R}\right)_\phi = \phi \left[ \frac{v_\alpha w_\alpha (1-S_\alpha)}{Z_\alpha} + \sum_{a=\alpha+1}^{A-1} \frac{v_a w_a (1-S_a)^{a-1}}{Z_a} \prod_{i=\alpha}^{a-1} S_i + \frac{v_A \bar{w}_A}{Z_A} \prod_{i=\alpha}^{A-1} S_i \right] \quad (2.4b)$$

The weight term representing the plus-group,  $\bar{w}_A$ , is the average over all age groups represented in the plus group. Provided growth is approximately linear for age classes older than the plus group,  $\bar{w}_A$  can be computed from the growth curve using the average age of the plus-group at equilibrium:

$$\bar{a}_A = \sum_{t=0}^{n-1} (A+i) S_A^t + \tau, \quad (2.5)$$

where again  $S_A$  is the probability of surviving from one year to the next and  $\tau$  is the time of the year during which the catch takes place. Equation (2.5) may be decomposed into two separate series,  $A \sum S^t = A(1-S_A^n)/(1-S_A)$ , and  $\sum t S_A^t = [(1-S_A^n)/(1-S_A) - (n-1)S_A^{n-1}]/(1-S_A)$ . Thus,

$$\bar{a}_A = A + \frac{1}{(1-S_A)} - \frac{n S_A^n}{(1-S_A^n)} - 1 + \tau, \quad (2.6a)$$

which in the limit as  $n$  goes to infinity reduces to

$$\bar{a}_A = A + \frac{S_A}{(1-S_A)} + \tau. \quad (2.6b)$$

PRO-2BOX uses the limit equations (2.4b and 2.6b) when a single stock or sex-specific analysis (below) is specified, thereby ensuring that the equilibrium calculations will be consistent with the results from the long-term projections for any given value of  $\phi$ .

### *Sex-specific analyses*

In this case expected yield from a given recruit depends also on the probability that the recruit is male or female:

$$\left(\frac{Y}{R}\right)_{\phi,k} = \phi \gamma_k \left[ \frac{v_{\alpha k} w_{\alpha k} (1-\delta_{\alpha k})(1-S_{\alpha k})}{Z_{\alpha k}} + \sum_{a=\alpha+1}^{A_k-1} \frac{v_{ak} w_{ak} (1-\delta_{ak})(1-S_{ak})^{a-1}}{Z_{ak}} \prod_{i=\alpha}^{a-1} S_{ik} + \left( \frac{v_{Ak} \bar{w}_{Ak} (1-\delta_{Ak})(1-S_{Ak})^{A_k-1}}{Z_{Ak}} \prod_{i=\alpha}^{A_k-1} S_{ik} \right) \frac{1}{1-S_{Ak}} \right] \quad (2.7)$$

where  $\gamma_k$  is the probability that a recruit is sex  $k$ . The average age of the plus-group (used for computation of  $\bar{w}_A$ ) is computed as in (2.6b), but with the sex-specific coefficients. Note that the age of the plus-group may vary between the sexes.

### Two-stock analyses

Limit equations analogous to (2.4b) and (2.6b) have not yet been derived for two-stock analyses, therefore PRO-2BOX uses variants of (2.3) with  $n$  set to 40. For the overlap model the equations are couched in terms of the yield (from both management zones) per recruit produced by spawners belonging to stock  $k$

$$\left(\frac{Y}{R}\right)_{\phi,k} = w_{\alpha k}[(1-T_{\alpha k})d_{\alpha k} + T_{\alpha k}d_{\alpha j}] + \sum_{a=\alpha+1}^n w_{ak}[(1-T_{ak})d_{ak} + T_{ak}d_{aj}] \prod_{i=\alpha}^{a-1} [(1-T_{ik})S_{ik} + T_{ik}S_{ij}] \quad (2.8)$$

where

$$S_{aj} = e^{-\phi_j v_{aj} - M_{aj}}$$

$$d_{aj} = \phi_j v_{aj} (1 - \delta_{aj}) \frac{1 - e^{-v_{aj} \phi_j - M_{aj}}}{v_{aj} \phi_j + M_{aj}}$$

Here the subscripts  $j$  and  $k$  index the management zone for the variables  $S$ ,  $d$ ,  $v$ ,  $M$  and  $\phi$ , whereas the subscript  $k$  indexes the stock for variables  $w$  and  $T$ .

The case of the diffusion model is somewhat problematic because the stock is identified with the management zone such that the effective number of recruits may change owing to the immigration of fish originating from in the other zone. Accordingly the appropriate yield per recruit equations require knowledge of the relative recruitment levels between zones, which of course might be expected to change with the level of fishing. At present, program PRO-2BOX computes yield per recruit on the assumption that the recruitment to each zone/stock is the same such that the yield per recruit calculations may be expressed as the recursion:

$$\left(\frac{Y}{R}\right)_{\phi,k} = \sum_{a=\alpha}^n w_{ak} d_{ak} [(1-\tilde{T}_{ak})\tilde{N}_{ak} + \tilde{T}_{aj}\tilde{N}_{aj}] \quad (2.9)$$

$$\tilde{N}_{ak} = \begin{cases} 1 & (a = \alpha) \\ \left(\tilde{N}_{a-1,k}(1-\tilde{T}_{a-1,k}) + \tilde{N}_{a-1,j}\tilde{T}_{a-1,j}\right)S_{a-1,k} & (a > \alpha) \end{cases}$$

where  $k$  and  $j$  now index the two management zones and  $d_{ak}$  is defined as in (2.8).

Alternatively, one could consider the yield per recruit spawned in a given management zone, which would require an additional subscript that keeps track of the zone where the recruit was spawned. This has yet to be programmed into PRO-2BOX.

### Spawn per recruit

The equations describing the expected number of eggs (or related measure) produced over the

lifetime of a recruit are similar to those describing the expected yield per recruit. For a single stock the relevant equation is

$$\left(\frac{S}{R}\right)_\phi = p_\alpha w_\alpha S_\alpha^\tau + \sum_{a=\alpha+1}^{A-1} p_a w_a S_a^\tau \prod_{i=\alpha}^{a-1} S_i + \frac{p_a \bar{w}_A S_A^\tau}{1 - S_A} \prod_{i=\alpha}^{A-1} S_i \quad (2.10)$$

$$S_a = e^{-\phi v_a - M_a}$$

where  $p_a$  is the proportion of age class  $a$  that is mature,  $v_a$  is the relative vulnerability of age class  $a$ ,  $\phi$  is the apical fishing mortality rate,  $w_a$  indexes the amount of spawning product produced (e.g., the weight at age) and  $\tau$  is the fraction of the year expired at the time of spawning. As before, the average amount of spawning product produced by members of the plus group,  $\bar{w}_A$ , may be computed from the average age of the plus-group given by (2.6b).

The spawn per recruit equations for sex-specific analyses are similar to (2.10) except that they are multiplied by the fraction belonging to that sex ( $\gamma_k$ ):

$$\left(\frac{S}{R}\right)_{\phi k} = \gamma_k \left( p_{\alpha k} w_{\alpha k} S_{\alpha k}^\tau + \sum_{a=\alpha+1}^{A_k-1} p_{ak} w_{ak} S_{ak}^\tau \prod_{i=\alpha}^{a-1} S_i + \frac{p_{Ak} \bar{w}_{Ak} S_{Ak}^\tau}{1 - S_{Ak}} \prod_{i=\alpha}^{A_k-1} S_{ik} \right) \quad (2.11)$$

The equations for the two-stock overlap model are

$$\left(\frac{S}{R}\right)_{\phi k} = p_{\alpha k} w_{\alpha k} [(1-T_{\alpha k}) S_{\alpha k}^\tau + T_{\alpha k} S_{\alpha j}^\tau] + \sum_{a=\alpha+1}^n p_{ak} w_{ak} [(1-T_{ak}) S_{ak}^\tau + T_{ak} S_{aj}^\tau] \prod_{i=\alpha}^{a-1} [(1-T_{ik}) S_{ik} + T_{ik} S_{ij}] \quad (2.12)$$

and the recursion for the two-stock diffusion model is

$$\left(\frac{S}{R}\right)_{\phi k} = \sum_{a=\alpha}^n p_{ak} w_{ak} S_{ak}^\tau [(1-\tilde{T}_{ak}) \tilde{N}_{ak} + \tilde{T}_{aj} \tilde{N}_{aj}] \quad (2.13)$$

$$\tilde{N}_{ak} = \begin{cases} 1 & (a = \alpha) \\ \left( \tilde{N}_{a-1,k} (1-\tilde{T}_{a-1,k}) + \tilde{N}_{a-1,j} \tilde{T}_{a-1,j} \right) S_{a-1,k} & (a > \alpha) \end{cases}$$

As in the case of equation (2.9), this formulation suffers if the relative recruitment levels in each zone differ (it assumes they are the same). It may be preferable to keep track of the spawning product per recruit spawned in a given management zone, which has not yet been programmed into PRO-2BOX.

## MANAGEMENT BENCHMARKS

### Maximum yield per recruit ( $F_{max}$ )

This benchmark is computed by a numerical search for the apical fishing mortality rate coefficient  $\phi$  that produces the highest yield per recruit (see equations 2.3 to 2.9):

$$\left(\frac{Y}{R}\right)_{max} = \max_{\phi} \left(\frac{Y}{R}\right)_{\phi} \quad (2.14)$$

The value of  $\phi$  that produces the maximum is termed  $F_{max}$ . In the case of the two-stock analyses, the maximization is performed with respect to apical fishing mortality rates for each stock,  $\phi_1$  and  $\phi_2$ , simultaneously. Note that the maximum level of yield per recruit generally cannot be sustained unless recruitment is independent of spawning biomass.

Related quantities output by PRO-2BOX that are sometimes used as proxies for the apical fishing mortality rate that produces the maximum sustainable yield ( $F_{MSY}$ , discussed below) are 75% of  $F_{max}$  ( $F_{0.75F_{max}}$ ) and the value that produces 90% of the maximum yield per recruit ( $F_{0.9Y/R}$ ). Note that there is no direct analog to  $F_{0.9Y/R}$  for two stocks inasmuch as an infinite combination of  $\phi_k$  values can achieve the same criteria. Accordingly, PRO-2BOX adopts the arbitrary procedure of setting  $\phi_1$  and  $\phi_2$  initially equal to  $F_{max,1}$  and  $F_{max,2}$  and reducing each by the same increment (0.001) until the corresponding yield per recruit value is less than or equal to 90% of  $(Y/R)_{max}$ .

### 10% Maximum slope of yield per recruit ( $F_{0.1}$ )

This benchmark is defined as the value of  $\phi$  where the slope of the yield per recruit curve is 10 percent of the slope at the origin. Inasmuch as  $F_{0.1}$  is always less than  $F_{max}$ , it is located by stepping back from  $F_{max}$  in steps of 0.001 and computing the value of the slope at that point by a forward difference approximation (with step size = 0.001). This procedure locates  $F_{0.1}$  to within an error of less than 0.005. Note that there is no direct analog to  $F_{0.1}$  for two stocks inasmuch as an infinite combination of  $\phi_k$  values can achieve the same criteria. Accordingly, PRO-2BOX adopts the arbitrary procedure of setting  $\phi_1$  and  $\phi_2$  initially equal to  $F_{max,1}$  and  $F_{max,2}$  and then reducing each by the same increment (0.001) until the corresponding slope of the yield per recruit curve is less than or equal to 10% of the slope at the origin.

### Spawning potential ratio ( $F_{x\%}$ )

One of the more popular management benchmarks is the equilibrium spawning potential ratio, defined as the ratio of the spawn per recruit expected at a given level of fishing  $\phi$  to the spawn per recruit under virgin conditions ( $\phi=0$ ):

$$SPR_{\phi} = \left(\frac{S}{R}\right)_{\phi} / \left(\frac{S}{R}\right)_0 \quad (2.15)$$

where the spawn per recruit (S/R) is calculated according to equations (2.10)-(2.13). PRO-2BOX searches for the values of  $\phi$  that produce SPR values of 20, 30 and 40 percent ( $F_{20\%}$ ,  $F_{30\%}$ ,  $F_{40\%}$ ).

Note that there is no direct analog to SPR for two stocks inasmuch as an infinite combination of  $\phi_k$  values can achieve the same criteria. An early version of PRO-2BOX solved for  $\phi_1$  by assuming the value for  $\phi_2$  was equal to  $F_{max,2}$ . However, in cases where the transfer rates are high, SPR values of 20% or lower have sometimes proven infeasible. Therefore,  $\phi_1$  and  $\phi_2$  are now set equal to  $F_{max,1}$  and  $F_{max,2}$  and then decremented by the same amount (0.001) until the corresponding SPR value is at the target level. Nevertheless, it must be reiterated that any method for two stocks is arbitrary.

### Maximum sustainable yield ( $F_{MSY}$ )

The concept of maximum sustainable yield remains one of the most pervasive tenets in fisheries management and is the stated goal of many management commissions. Estimates of this quantity were originally associated with production models (e.g., Pella and Tomlinson 1969), but can be derived from age-structured models provided one can express the expected equilibrium recruitment ( $N_{\alpha,\phi}$ ) as a function of the equilibrium fishing mortality rate  $\phi$  (see Shepherd, 1982; Restrepo et al., 1994):

$$MSY = \max_{\phi} \left\{ N_{\alpha,\phi} \left( \frac{Y}{R} \right)_{\phi} \right\} \quad (2.16)$$

In the simplest case, where recruitment is assumed to be a constant value  $\omega$ ,

$$MSY = \omega \left( \frac{Y}{R} \right)_{max} \quad (2.17)$$

In the cases where recruitment is assumed to follow the two-line (hockey stick) relationship,

$$N_{\alpha,\phi} = \begin{cases} \omega SSF_{\phi} / \beta & SSF_{\phi} < \beta \\ \omega & SSF_{\phi} \geq \beta \end{cases} \quad (2.18)$$

the solution is the same as (2.17), provided the value of  $(S/R)\phi$  is greater than or equal to the slope of the descending limb of the curve ( $\omega/\beta$ ). Values of  $(S/R)\phi$  less than  $\omega/\beta$  are, by definition, not sustainable. The most straightforward way to deal with this problem is to make multiple projections with various levels of  $\phi < F_{max}$  and select the value of that produces the greatest yield once an equilibrium is reached (perhaps after 100 years or so, depending on the life history of the animal).

If recruitment is assumed to follow the Beverton and Holt (1957) or Ricker (1954) spawner-recruit curves, the equilibrium recruitment expected under a given level of  $\phi$  may be expressed in terms of the spawn per recruit statistic described earlier. Note that, at equilibrium,  $SSF_{\phi} = N_{\alpha,\phi}(S/R)_{\phi}$ ; therefore

$$N_{\alpha,\phi} = \begin{cases} \frac{\omega SSF_{\phi}}{\beta + SSF_{\phi}} = \frac{\omega \left(\frac{S}{R}\right)_{\phi}}{\frac{\beta}{N_{\alpha}} + \left(\frac{S}{R}\right)_{\phi}} = \omega - \frac{\beta}{\left(\frac{S}{R}\right)_{\phi}} & \text{Beverton / Holt} \\ \omega SSF_{\phi} e^{-\beta SSF_{\phi}} = \omega \left(\frac{S}{R}\right)_{\phi} N_{\alpha} e^{-\beta \left(\frac{S}{R}\right)_{\phi} N_{\alpha}} = \frac{\log_e \left( \omega \left(\frac{S}{R}\right)_{\phi} \right)}{\beta \left(\frac{S}{R}\right)_{\phi}} & \text{Ricker} \end{cases} \quad (2.19)$$

Hence, the *MSY* may be found by maximizing the following expressions over  $\phi$

$$\begin{cases} \left( \frac{Y}{R} \right)_{\phi} \left( \omega - \beta / \left( \frac{S}{R} \right)_{\phi} \right) & \text{Beverton / Holt} \\ \left( \frac{Y}{R} \right)_{\phi} \left( \log_e \left( \omega \left( \frac{S}{R} \right)_{\phi} \right) / \beta \left( \frac{S}{R} \right)_{\phi} \right) & \text{Ricker} \end{cases} \quad (2.20)$$

(see Shepherd, 1982; Restrepo et al., 1994). PRO-2BOX uses the Nelder-Mead simplex algorithm to accomplish the search (see discussion of numerical optimization in Porch, 2002). Strictly speaking, the  $\omega$  terms in (2.20) may need to be multiplied by a factor  $\exp(\sigma^2/2)$  to correct for the lognormal bias discussed below in the section on stochastic dynamics, but this has not been done here because it has not been done for the ICCAT assessments PRO-2BOX was designed to emulate.

Of course it is also possible to compute the sustainable yields for benchmarks other than *MSY* by simply applying (2.20) to the corresponding value of  $\phi$  (e.g.,  $F_{0.1}$  or  $F_{30\%}$ ).

## STOCHASTIC DYNAMICS

Stochastic variations in the population dynamics may be introduced by projecting bootstrapped runs of the original assessment model (read from a series of binary files discussed in chapter 3) and by incorporation of process error in recruitment. The latter is accomplished in two ways: by fitting separate spawner-recruit relationships to each bootstrap run (when available) and by allowing recruitment to deviate from the prediction of the spawner-recruit curve.

### Fitting the spawner-recruit curve to data

The present version of PRO-2BOX can express future recruitment according to four basic models: constant, two-line (hockey stick), Ricker and Beverton/Holt. In the case of the first two types, the fitting procedure merely involves the computation of arithmetic or geometric mean levels

of historical recruitment and spawning biomass (for more details see the discussion of the spawner-recruit relationship file in Chapter 3). When the Ricker or Beverton/Holt models are used, however, the parameters are estimated from the inputted historical values of recruitment ( $N_a$ ) and spawning product ( $SSF$ ) by nonlinear regression assuming either an additive (normal) or multiplicative (lognormal) error structure (see line 44 of the control file).

In the case of an additive error structure the parameters are estimated by minimizing the concentrated likelihood function

$$\frac{n}{2} \log_e \sigma^2 + \frac{1}{2\sigma^2} \sum_{i=Y_0}^{Y_\Omega} \left( N_{\alpha,i} - \hat{N}_\alpha(SSF_{i-\alpha} | \beta, \omega) \right)^2 \quad (2.21)$$

$$\sigma^2 = \frac{1}{n} \sum_{i=Y_0}^{Y_\Omega} \left( N_{\alpha,i} - \hat{N}_\alpha(SSF_{i-\alpha} | \beta, \omega) \right)^2$$

where  $Y_0$  and  $Y_\Omega$  are the first and last years of recruitment observations used in the fitting ( $n = Y_\Omega - Y_0 + 1$ ) and  $\hat{N}_\alpha(SSF_{i-\alpha} | \beta, \omega)$  is the recruitment predicted by the chosen spawner/recruit curve with parameters  $\omega$  and  $\beta$ . Note that the values of  $\omega$  and  $\beta$  that minimize (2.21) are equivalent to the least-squares estimates.

In the case of the multiplicative error structure the parameters are estimated by minimizing the concentrated likelihood function

$$\frac{n}{2} \log_e \sigma^2 + \frac{1}{2\sigma^2} \sum_{i=1}^n \left( \log_e \{ N_{\alpha,i} \} - \log_e \{ \hat{N}_\alpha(SSF_{i-\alpha} | \beta, \omega) \} \right)^2 \quad (2.22)$$

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n \left( \log_e \{ N_{\alpha,i} \} - \log_e \{ \hat{N}_\alpha(SSF_{i-\alpha} | \beta, \omega) \} \right)^2$$

which is equivalent to the least-squares solution using logarithmically transformed variates. Here it is important to realize that the values of  $\omega$  and  $\beta$  that minimize (2.22) do not give the expectation of recruitment  $E[N_{\alpha,i}]$ , but the expectation of the *logarithm* of recruitment  $\mu = E[\log_e \{ N_{\alpha,i} \}]$ . The expected recruitment is given by  $\exp\{\mu + 0.5\sigma^2\}$ . This is important to remember for the next section.

In some instances there may be too little contrast or too much scatter in the data to reliably estimate the shape of the spawner-recruit curve, as when aberrant solutions arise during bootstrapping. In order to avoid situations where the maximum recruitment level  $\omega$  is estimated to be unreasonably large, the following optional constraint may be added to the likelihood expressions above:

$$\begin{cases} \frac{1}{\zeta^2} (\omega - \tilde{\omega})^2 & \text{if } \omega > \tilde{\omega} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{where } \tilde{\omega} = \begin{cases} \max_y \{N_{\alpha y}\} & \text{option 1} \\ \frac{1}{(Y_2 - Y_1 + 1)} \sum_{i=Y_1}^{Y_2} N_{\alpha i} & \text{option 2} \end{cases} . \quad (2.23)$$

$$\zeta^2 = \frac{1}{n-1} \sum_{y=Y_0}^{Y_\Omega} (N_{\alpha y} - \bar{N}_\alpha)^2$$

$$\bar{N}_\alpha = \frac{1}{n} \sum_{i=Y_0}^{Y_\Omega} N_{\alpha i}$$

Here  $Y_1$  and  $Y_2$  are years specified by the user (see discussion of the spawner-recruit relationship file). In the case of a multiplicative error structure the observed recruitments in the calculations of (2.23) would be replaced by their log transformed values. The rationale for this constraint is that, if the variance in observed recruitment ( $\zeta^2$ ) is much larger than the variance about the fitted line ( $\sigma^2$ ), then the data probably contain enough information to produce meaningful estimates of  $\omega$  and the penalty for large values of  $\omega$  should be relatively small. On the other hand, if the two variances are about the same then the fitted curve does nothing to explain recruitment and the penalty for large  $\omega$  should be stronger. Moreover, the penalty becomes relatively less important as the number of data points used in the fitting increases.

### Autocorrelated deviations in recruitment from the expectation

Future recruitment  $N_{\alpha y}$  is allowed to deviate from its expectation  $E[N_{\alpha y}]$  as a first-order autocorrelated process that is either additive or multiplicative according to the choice for the estimation procedure above. Generally the multiplicative structure is preferred because it does not admit negative recruitments and because it allows the variance in recruitment to increase with its expectation.

Additive errors are accommodated by drawing at random from the normal distribution centered on the expectation with variance equal to  $\sigma^2$  (which may be prescribed by the user or estimated as in equation 2.21). In practice this is accomplished by multiplying a standard normal deviate  $\varepsilon$  by the value of  $\sigma$ .



$$\begin{aligned}
N_{\alpha y} &= E[N_{\alpha y}] + \eta_y \\
\eta_y &= \rho\eta_{y-1} + \sigma\varepsilon_y \\
\varepsilon_y &\sim \text{Normal}(0,1)
\end{aligned}
\tag{2.24}$$

Note that  $\sigma^2$  refers to the variance of the random component only. The total variance of the autocorrelated recruitment deviations is  $\xi^2 = \sigma^2 / (1 - \rho^2)$ .

In the case of multiplicative errors, future recruitments are drawn from the lognormal distribution with parameters  $\mu$  and  $\sigma$  (now the standard error of the random component of the logged deviations), where  $\mu = E[\log_e N_{\alpha y}]$ . In practice this is accomplished by noting that if a variate  $x$  is lognormal distributed with parameters  $\mu$  and  $\sigma$ , then  $\log_e x$  is normal distributed with parameters  $\mu$  and  $\sigma$ . Hence,

$$\begin{aligned}
N_{\alpha y} &= e^{\mu + \sigma\eta_y} \\
\eta_y &= \rho\eta_{y-1} + \sigma\varepsilon_y \\
\varepsilon_y &\sim \text{Normal}(0,1)
\end{aligned}
\tag{2.25}$$

It is important to note that the expectation of the random variates generated in (2.25) is not  $e^\mu$  (the median of the lognormal distribution), but rather  $e^{\mu + 0.5\sigma^2}$  (the true mean). Accordingly, the average of a set of recruitment projections should give an unbiased picture of the expected trend in recruitment (all other things being equal) provided the parameter estimates used predict  $E[\log_e N_{\alpha y}]$ , as in (2.22), rather than  $E[N_{\alpha y}]$ .

## MULTIPLE FLEETS

Many stocks are fished by several fleets employing different gears or operating in different management zones. Often there may be a desire to regulate these fleets differently, either by reducing their total allowable catch or by altering their selection practices. Thus, in order to project the potential outcomes of such regulations accurately, one needs to model each fleet separately. PRO-2BOX calculates the historical fishing mortality rate attributable to the  $i$ 'th fleet from the overall fishing mortality rate ( $F_{ay}$ ) and the fleet-specific catches ( $C_{iay}$ ) as follows:

$$F_{iay} = \frac{C_{iay}}{\sum_i C_{iay}} F_{ay} \quad .
\tag{2.26}$$

As in the case of a single fleet, PRO-2BOX assumes that future  $F_{iay}$  matrices are separable into age-specific relative-vulnerability vectors  $v_{ia}$  and a year-specific apical fishing mortality rate  $\phi_i$  (the maximum  $F$  over all age classes). The vulnerability vector may be specified manually or computed from historical partial fishing mortalities  $F_{iay}$ . The apical fishing mortality rates for each fleet may be specified manually, set to some average of the corresponding historical estimates, or computed

so as to achieve prescribed total allowable catch.

The software does not compute multi-fleet benchmark statistics. The statistics that are produced are based on an overall vulnerability vector calculated from the overall fishing mortality and discard rates (all fleets combined). Accordingly, an error message is produced when the user attempts to run multi-fleet projections with the values of  $\phi_i$  fixed to one of the benchmark values.

# 3. INPUT FILES

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Program PRO-2BOX always requires two ASCII text files: a control file containing most of the technical specifications for the projections and a quota file specifying the total allowable catch or fishing mortality rate for each year in the projection. A template for each of these files appears in an appendix. The explanation for each line item in the appropriate appendix is then given under the corresponding heading below.

Note that each of the files is read in free-format fashion, that is, the input data need not be in any particular column. Of course, if there are multiple entries on one line, it is necessary to enter the data in the proper sequence. For example, catch-at-age information must be entered in the sequence {year, catch-at-youngest-age, catch-at-youngest-age+1, ..., catch-at-oldest-age}.

Comment lines may be inserted anywhere in the file provided they are preceded by a # symbol in the first column. Data placed after a # symbol will not be read. Comments may also appear on the same line as the inputs, provided they appear only at the end of the line (after all required inputs). For example, the following comments are acceptable:

```
# First & last years in data file
# |         |         Last year in projections
  1975      1999      2040
```

or

```
1975      1999      2040      First & last years in data, last year of projections
```

In contrast, the comment forms below are unacceptable:

```
# First & last years in data file
# |         |         Last year in projections
  1975      1999      2040
```

or

```
1975 (first year in data) 1999 (last year in data) 2040 (projection year)
```

PRO-2BOX also reads nine other files containing the historical data and other information (abundance, fishing mortality rate, natural mortality rate, catches, weights etc). These nine files may either be ASCII text files (for deterministic inputs) or binary direct access files (for multiple inputs such as from bootstrap runs from VPA-2BOX). They are discussed below after the sections on the control and quotas files.

Finally, if you specify a negative integer on line 13 of the control file (discussed below), then the program will look for an ASCII text file named BAD.OUT that contains a list of the bootstrap runs you wish to exclude from the projections. The integer indexing the bad loop must be the first

entry on each line with any comments appearing after this integer or at the end of the file.

## CONTROL FILE: Appendix 1

This is the only file PRO-2BOX will prompt the user for. It contains the file names of all the other input files and most of the model specifications. What follows is a line by line explanation of the entries in Appendix 1.

<u>Line</u>	<u>Explanation</u>
<b>1 - 10</b>	<b>Comments</b> preceded by the # symbol in the first column. <i>Specifications common to both stocks/sexes</i>
<b>11</b>	<b>The class of model being used</b> (1=diffusion, 2=overlap; 3=sex-specific). If only 1 stock (one or two sexes) is considered, then the overlap and diffusion models are the same.
<b>12</b>	<b>Number of population groups to be considered</b> (1=single stock with both sexes lumped together, 2=two stocks/zones or two sexes).
<b>13</b>	<b>Number of bootstrap replicates to be projected.</b> Enter 0 if only a single deterministic run is desired (the first record in the binary input files should contain the deterministic results from the stock assessment algorithm (see below). Enter a negative integer if you want to cull the bootstrap runs listed in the file BAD.OUT (see above).
<b>14</b>	<b>Width of confidence interval in percent (CI).</b> The program generates confidence limits using the percentile method, whereby each bootstrap replicate is ranked in ascending order. For example, entering 80 for the CI when there are 100 bootstrap replicates will cause the lower confidence limit to be set equal to the bootstrap replicate with the tenth lowest value and the upper confidence interval to be set equal to the replicate with the tenth highest value.
<b>15</b>	<b>Seed used to initiate the random number generator</b> for stochastic projections (must be a negative integer). This feature was originally designed to allow distinct bootstrap replicates to be generated on several different machines simultaneously, which could later be combined into a single larger bootstrap analysis. Such is seldom necessary with today's faster PC's.
<b>16</b>	<b>Replace the historical estimates of recruitment for the last <math>n</math> years (<math>N_{ay}</math>)</b> with values estimated from the spawner-recruit relationship $^R N_{ay}$ (see spawner-recruit relationship file). The program then uses the following recursion to compute the fishing mortality rate vector necessary to reproduce the observed catches over the life of the cohort (up to the last year in the data):

$$F_{ay} - \frac{C_{ay}(F_{ay} + M_a)}{N_{ay}(1 - e^{-F_{ay} - M_a})} = 0 \quad (3.1)$$

$$N_{a+1,y+1} = N_{ay} e^{-F_{ay} - M_a} \quad (3.2)$$

where (3.1) is solved by Newton-Raphson iteration and the recursion is initiated by

substituting the replacement value  $^R N_{\alpha y}$  for  $N_{\alpha y}$  in (3.1). This procedure provides a potentially objective means of replacing the recruitment estimates for the most recent years in the time series, which tend to be poorly estimated. Analogous equations are developed for the overlap and diffusion models for two intermixing stocks.

In some cases it may happen that the new recruitment value is too small to support the observed catches, particularly when stochastic variations are introduced. In such cases the program sets the new recruitment equal to the value that allows the observed catches to be achieved with an apical fishing mortality rate of  $3.0 \text{ yr}^{-1}$ . Geromont and Butterworth (2001) advocate resampling from the recruitment distribution repeatedly until a value is drawn that allows the observed catches to be realized, which necessarily imparts a greater positive bias than the adjustment used here. In practice, however, the difference between the two approaches will be negligible unless the expected recruitment is very low and the variance very high.

17 **Stock/sex to use when computing MSY and maximizing yield per recruit.** The search algorithm will find the apical fishing mortality rates that maximize the yield per recruit or maximum sustainable yield of the selected stock/sex. (An entry of '3' tells the program to maximize the combined yield of both stocks/sexes.)

18 **Sex-specific options.**

- 1 Recruitment depends on fecundity of sex 1 (sex 2 is not limiting)
- 2 Recruitment depends on fecundity of sex 2 (sex 1 is not limiting)
- 3 Recruitment depends on combined spawning products of both sexes

19 **Fraction of new recruits (age  $\alpha$ ) belonging to sex 1.** Enter a value  $> 0$  and  $< 1$ .

20 **Method of computing the weight and fecundity of each age class.**

- 0 Weights computed from growth curve for all ages all years
- 1 Observed weights used for all ages except the plus group in projection years, which is calculated by inverting the growth curve. Weights of younger age-classes are set equal to the values observed during the last year of data.
- 2 Observed weights used for all ages. Weights in projection years are set equal to the values observed during the last year of data.

25 **The first and last years in the data file followed by the last year in the projections.**

31 **The youngest ( $\alpha$ ) and oldest ( $A$ ) age classes in the data file.** The oldest age class is assumed to be a plus-group (i.e., it represents ages  $A$  and older). In the case of two-stock or two-sex projections, a total of three entries are required: one entry for  $\alpha$  (because it must be the same for both groups) and two entries for  $A$  (which may differ between sexes, but not between stocks).

36 **The vulnerability specifications.** A negative entry tells the program to use the vulnerability vector listed in the vulnerability input file (see below). Alternatively, two positive integers are interpreted as the endpoints of the range of years to be used in computing the vulnerability vector  $v_a$  from a weighted geometric mean of historical estimates of fishing mortality rate:

$$v_a = \frac{\lambda_a e^{\frac{1}{n} \sum \log_e F_{ay}}}{\max_a \{ \lambda_a e^{\frac{1}{n} \sum \log_e F_{ay}} \}} \quad . \quad (3.3)$$

Note that the age-specific vector of geometric means is normalized by dividing the through by its maximum value over all ages, creating a relative vulnerability vector with a maximum value of one. This method essentially assumes that the future vulnerability of the stock to the fishery will be equivalent to the average selectivity over the range of years selected. The weighting factor  $\lambda_a$  is contained in the vulnerability input file and is used principally to modify the future vulnerability vector to account for such things as proposed minimum size limits (see discussion of vulnerability file below).

In the case of two sexes there is only one apical fishing mortality rate and therefore the vulnerability vectors for each sex  $s$  are relative to one another and obtained as

$$v_{sa} = \frac{\lambda_{sa} e^{\frac{1}{n} \sum \log_e F_{say}}}{\max_{a,s} \{ \lambda_{sa} e^{\frac{1}{n} \sum \log_e F_{say}} \}} \quad . \quad (3.4)$$

In the case of two stocks, there are two distinct apical fishing mortality rates ( $\phi_k$ ,  $k=1,2$ ) and the vulnerability vectors for each stock  $k$  are independent:

$$v_{ka} = \frac{\lambda_{ka} e^{\frac{1}{n} \sum \log_e F_{kay}}}{\max_a \{ \lambda_{ka} e^{\frac{1}{n} \sum \log_e F_{kay}} \}} \quad . \quad (3.5)$$

When multiple fleets are considered equations (3.3) - (3.5) remain the same except for an additional subscript  $i$  indexing the fleet. Inasmuch as there are fleet-specific apical fishing mortality rates, the vulnerability vector for each fleet is normalized by its own maximum value, e.g., for one stock,

$$v_{ia} = \frac{\lambda_{ia} e^{\frac{1}{n} \sum \log_e F_{iay}}}{\max_a \{ \lambda_{ia} e^{\frac{1}{n} \sum \log_e F_{iay}} \}} \quad . \quad (3.6)$$

The overall vulnerability vector used to compute the benchmark statistics is computed according to equations (3.3), (3.4) or (3.5) as appropriate.

41

**Range of years (first and last) defining the recruitment and spawning stock data** to be used in calculations pertaining to spawner-recruit relationship (see discussion of spawner-recruit input file).

- 44 **Error structure of projected recruitment** and spawner-recruit regression:
- 1 Multiplicative (lognormal)
  - 2 Additive (normal)

The choice of error structure applies to both the stochastic projections and the fitting procedure (see section on Stochastic dynamics above for more details).

*Specifications unique to each stock/sex*

- 48 **Number of fleets represented in the data file fishing on stock/sex 1** (note: this number should be the same for both sexes in a sex-specific analysis, but may differ between stocks in a two-stock analysis).

- 49 **Average age of the plus-group at the beginning of the last year in the data.** Entering a positive value tells the program to use the value of the input. Entering a negative value will cause the program to determine the average age from the average weight of the plus group observed in the catch of fleet 1 by inverting the growth equation.

- 50 **The relative fraction of each age class that spawns every year ( $\theta_a$ ).** This vector is used to compute the spawning stock fecundity (see Tables 1 and 2) and therefore should include any age-dependent changes in spawning potential. There should be one value between 0 and 1 for each age class.

- 62 **Growth curve parameters for determining fecundity (biomass) of spawners.** The first entry specifies the **curve type**, which may take two basic forms:

1 Chapman-Richards equation,

$$l_t = l_\infty(1 - me^{-k(a + date/12 - offset/12 - t_0)})^{1/m} \quad \text{where } m \neq 0$$

$$w_t = cl_t^b \tag{3.7}$$

2 Gompertz equation,

$$w_t = w_\infty e^{-e^{-k(a + date/12 - offset/12 - t_0)}} \tag{3.8}$$

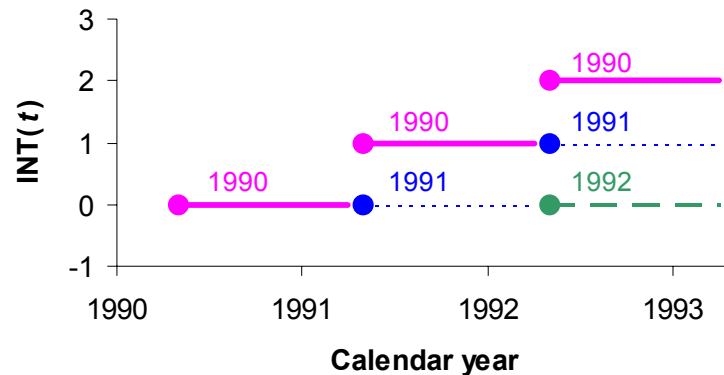
Here  $a$  is an integer indexing the age class of the animal as defined in the stock assessment model. Note that the Chapman-Richards option reduces to the von Bertalanffy curve when the parameter  $m$  is set to 1.

The second through fourth entries correspond to the parameters  $l_\infty$  ( $w_\infty$ ),  $k$ , and  $t_0$ . The fifth entry is the skew parameter  $m$  and the sixth and seventh entries correspond to parameters  $c$  and  $b$  of the weight-length relationship (3.7). The entries for  $m$ ,  $c$  and  $b$  are superfluous when the Gompertz curve is selected, but dummy values must still be inserted. The eighth entry is the time of the year corresponding to the **date** of the spawning event (usually the peak of the spawning season) in terms of elapsed months.

The ninth and final entry is an **offset** parameter meant to correct for the difference in months between the ‘true’ age used for the growth curve ( $t$ ) and the age defined within the assessment model (VPA age). For example, suppose the data are reported by calendar year (January through December), but spawning occurs on May 1<sup>st</sup> (4 months into the calendar year). One way to ensure the assessment properly tracks distinct yearclasses is to assign animals with true ages between an integer

value  $a-4/12$  and  $a+8/12$  to age class  $a$  and animals with true ages between  $a+8/12$  and  $a+1+4/12$  to age class  $a+1$ . In other words,  $a$  would be defined as the integer part of  $t+4/12$  as illustrated in Figure 1 below. Accordingly, when translating back to true age from the VPA age one must subtract the offset parameter; i.e., the true age of the animal at the beginning of the  $m$ th month of the calendar year is  $a+m/12-4/12$  ( $a$  now representing the integer-valued age class from the VPA). In this example the *offset* parameter is +4 (four months elapsed). Often times the *offset* will be equal to the spawning *date* (eighth entry above), depending upon exactly how the investigator chooses to index the yearclasses.

Care must be taken to make sure the sign of the *offset* is correct inasmuch as it is the amount that must be subtracted from the VPA age in order to arrive at the true age (see 3.7 and 3.8). In the above example the offset is +4. However, suppose the convention had been to assign fish between the ages of  $a-4/12$  and  $a+8/12$  to age class  $a-1$ . In that case the true age of an animal belonging to age class  $a$  at the beginning of the  $m$ th month of the calendar year is  $a+m/12-4/12+1$ . Accordingly, the offset is -8, because  $8/12$  must be added (i.e.,  $-8/12$  must be subtracted) from the VPA age.



**Figure 1.** Integer part of true age  $t$  with time (in years) for three year classes, each born on May 1<sup>st</sup> of the corresponding calendar year (i.e., after  $4/12$  of the calendar year have elapsed). The solid, dotted and dashed lines refer to the respective yearclasses born in 1990, 1991 and 1992. The solid circles indicate the anniversaries of the May 1<sup>st</sup> birth dates. Note that, for any given calendar year, animals of age  $\{8/12 \leq t < 1\}$  belong to the same yearclass as those of age  $\{1 \leq t < 1+8/12\}$ . Thus, one can preserve yearclasses within the stock assessment model by defining the age class  $a$  as the integer part of  $t+4/12$ .

Note that the Gompertz, von Bertalanffy and Chapman-Richards equations discussed above are usually used to determine weight from age, which is often used as a proxy for fecundity at age. However, in many cases these equations can also be fit directly to other measures of fecundity such as gonad weight or number of eggs produced. In circumstances where these curves do not provide an adequate fit, one can always compute a fecundity vector based on



other equations and enter it as data in the weight at age file (making sure to set the entry in line 20 to 2). The only draw back to this approach of course is that the average fecundity of the plus group cannot change, whereas one might expect it to increase along with the average age under reduced fishing pressure).

**63** **Growth curve parameters for determining weight of catch.** The format is exactly the same as for line 62, the only difference is that these parameters apply to the catch of fleet 1 (for example, the *date* parameter refers to the month of the calendar year at the peak of the catch) . A distinct set of specifications should be included for each fleet. If there are five fleets there should be five corresponding lines with growth parameters. Note that the parameters for fleet 1 are used to compute the overall benchmark statistics; therefore the fleet designated first should be the one with growth parameters most reflective of the catch of the overall fishery. Alternatively, one could create a dummy fleet 1 with zero catch.

**64-66** **Here the sequence from lines 48-63 would be repeated for stock/sex 2**, with corresponding parameters (in this example there is in view only a single stock with both sexes combined, therefore no information on the ‘second’ stock/sex is required).

*Specifications of files containing additional data and information*

**71-82** The two entries on each line give the **format type** (ASCII or direct access) and **name** for each of ten additional files read by PRO-2BOX. The details are given below under each specific file type heading.

## QUOTA FILE: Appendix 2

An example of the quota file is presented in Appendix 2. This file contains the specifications for future limits on the landings in weight (TAC) and fishing mortality rates. It is important to realize that PRO-2BOX employs both types of limits as if both were the expected result of management actions. Therefore, if the only effect of interest in a particular year is the TAC, then the fishing mortality rate coefficient should be set to a very large value (and vice-versa).

<u>Line</u>	<u>Explanation</u>
4	<b>Number of management scenarios.</b> Multiple scenarios with different combinations of fishing mortality rate limits and TAC's may be applied.
5-7	<b>Comments.</b> A descriptive header identifying the first scenario (not required).
13-15	<b>Specifications for TAC's for first scenario.</b> The first entry is an integer indexing the stock or zone; if the projections are for a single stock/zone you would only enter 1's in this column as the quotas are <i>not</i> sex-specific. The second entry is an integer indexing the fleet (enter 1 if there is only one fleet). The remaining entries give the TAC's for each projection year. The TAC's are specified in thousand units. Thus, if the weights specified by the growth curve or in the weight file are measured in kilograms [pounds], then the TAC's should be specified in metric tons [thousands of pounds]. In this example the TAC's are set to an arbitrarily large value with the expectation that the fishing mortality limits specified next will be the primary control mechanism.
16	<b>A negative value</b> tells the program to stop reading TAC values and go on to read fishing mortality rate limits. Any stocks/zones or fleets that were not represented in the preceding lines are assumed to have TAC's of zero.
22-24	<b>Specifications for apical fishing mortality rate (<math>\phi</math>) limits for first scenario.</b> The first entry is an integer indexing the sex or stock; if the projections are for a single stock you would only enter 1's in this column as the limits are <i>not</i> sex-specific. The second entry is an integer indexing the fleet (enter 1 if there is only one fleet). The remaining entries give the $\phi$ limits (in units of $\text{yr}^{-1}$ ) for each projection year. In the example file the first value is -999, which tells the program that the apical fishing mortality rate in the first projection year should be set to the geometric mean of the historical estimates for the years specified in the control file (line 36) or the estimate from the last year of the data file (if line 36 has a negative entry). The remaining values are 0.1, which tells the program to fix $\phi$ to 0.1 for the balance of the projection years. There are several options for controlling $\phi$ :

<u>Entry</u>	<u>Result</u>	
-0.1	$\phi = F_{0.1}$	achieves 10% of slope in $y/r$ at origin
-0.75	$\phi = F_{75F_{max}}$	75% of $F_{max}$
-0.9	$\phi = F_{90Y_{max}}$	achieves 90% maximum yield per recruit
-1	$\phi = F_{max}$	achieves maximum yield per recruit
-2	$\phi = F_{MSY}$	achieves maximum sustainable yield
-20	$\phi = F_{20\%}$	achieves an SPR of 20%

-30	$\phi = F_{30\%}$	achieves an SPR of 30%
-40	$\phi = F_{40\%}$	achieves an SPR of 40%
+x	$\phi = x$	positive entry is desired value of $\phi$
-999	$\phi = F_{current}$	$\phi$ set to historical values

$$= \begin{cases} \max_a \left[ \lambda_a e^{\frac{1}{n} \sum \log_e F_{ay}} \right] & \text{line 36 of control file} > 0 \\ \max_a F_{a, \text{last year in data file}} & \text{otherwise} \end{cases}$$

25      **A negative value** tells the program to stop reading  $\phi$  limits for that scenario and go on to read the TAC's for the next scenario. Any stocks/zones or fleets that were not represented in the preceding lines are assumed to have  $\phi$  limits of zero.

26-46      This section repeats the sequence of lines 5-25 above to define a second scenario where the TAC is set to 1000 for every projection year and the  $\phi$  limit is set to 2.0 yr<sup>-1</sup>. In this case the TAC is expected to be the limiting factor, but if the future abundance declines sufficiently it may not always be possible to achieve the TAC except with unrealistically high  $\phi$  values. Accordingly, the maximum value  $\phi$  can attain is capped at 2.0 yr<sup>-1</sup>.

## ABUNDANCE FILE

This file contains the estimates of historical abundance produced by the assessment model. There are two file type options: an ASCII text file or a binary direct access file (such as produced by VPA-2BOX). The data entries in the ASCII file must be ordered by stock and by year as follows:

1	1994	39192.27355	31123.30448	15882.59242	7941.113854	43214.92703
1	1995	35308.48328	29034.35036	17080.83165	6457.380194	32196.44784
1	1996	32059.34889	26157.16776	17610.22368	9374.159166	25125.80978
2	1994	16796.68866	14726.65355	11211.34074	7566.689768	62609.83132
2	1995	15132.20712	13738.22047	10909.77328	7515.186444	42564.21163
2	1996	13739.72095	12376.82032	10177.52404	7313.039725	30374.69035


The lines for stock (sex) 1 must always precede those for stock (sex) 2 and the lines for year  $y$  must always precede year  $y+1$ . Comments may only be inserted at the end of a line or the end of the file, after all data (as illustrated above). Every stock/year/age combination must have an entry associated with it (i.e., dummy values should be substituted for missing data).

The binary direct access file must have a record length of  $[4*(Y-y_0+1)*(A-\alpha+1)*K]$ , where  $y_0$  and  $Y$  are the first and last years of historical estimates,  $\alpha$  and  $A$  are the first and last age classes, and  $K$  is the number of stocks/sexes. Each abundance estimate  $N$  should be stored as a 4-bit single precision variable written in the following order:  $((N(k, a, y), y=y_0, Y), a=\alpha, A), k=1, K)$ .

## FISHING MORTALITY RATE FILE

This file contains the estimates of historical fishing mortality rate produced by the assessment model. There are two file type options: an ASCII text file or a binary direct access file (the formats of both are the same as for the abundance discussed file above).

## WEIGHT FILE

This ASCII text file contains the estimates for the average weight of each age class at the time of spawning and at the time when most of the catch is made by each fleet. The data entries must be ordered by stock/sex, fleet and year as follows:

1	0	1994	2.722920559	8.940930072	19.82758181	35.677741	126.5819518
1	0	1995	2.722920559	8.940930072	19.82758181	35.677741	148.3459004
1	0	1996	2.722920559	8.940930072	19.82758181	35.677741	162.8575871
1	1	1994	3.522920559	9.140930072	21.02751885	37.211333	140.1111113
1	1	1995	3.522920559	9.140930072	21.02722086	37.211333	150.7777004
1	1	1996	3.522920559	9.140930072	21.02743982	37.211333	170.6775871
1	2	1994	3.522920559	9.140930072	21.02747883	37.211333	145.4519518
1	2	1995	3.522920559	9.140930072	21.02738989	37.211333	146.2234454
1	2	1996	3.522920559	9.140930072	21.02739881	37.211333	187.3333333
2	0	1994	5.710659763	13.89844102	26.11397792	42.13217522	96.58269052
2	0	1995	5.710659763	13.89844102	26.11397792	42.13217522	114.7660805
2	0	1996	5.710659763	13.89844102	26.11397792	42.13217522	127.9970475
2	1	1994	5.710659763	13.89844102	26.11397792	42.13217522	96.58269052
2	1	1995	5.710659763	13.89844102	26.11397792	42.13217522	114.7660805
2	1	1996	5.710659763	13.89844102	26.11397792	42.13217522	127.9970475
2	2	1994	5.710659763	13.89844102	26.11397792	42.13217522	96.58269052
2	2	1995	5.710659763	13.89844102	26.11397792	42.13217522	114.7660805
2	2	1996	5.710659763	13.89844102	26.11397792	42.13217522	127.9970475

weight at age (from youngest to oldest)  
year  
fleet (fleet=0 indicates weights at spawning time)  
integer specifying stock or sex

The lines for stock (sex) 1 must always precede those for stock (sex) 2, the lines for fleet  $i$  must always precede fleet  $i+1$ , and year  $y$  must always precede year  $y+1$ . Comments may only be inserted at the end of a line or the end of the file, after all data (as illustrated above). Every stock/fleet/year/age combination must have an entry associated with it (i.e., dummy values should be substituted for missing data). Note that in the present example there are two stocks (or sexes) with two fleets covering three years (1994-1996). The zero entry in the fleet column tells the program that the entries to the right refer to the average weights during the spawning season.

## CATCH FILE

This ASCII text file contains the estimates for the total catch of each age class made by each fleet (including animals discarded dead) in each management zone. The data entries must be ordered by management zone/sex, fleet and year as follows:

```
1 1      1994  3385.974398  9361.648552  7330.720617  3665.276142  7123.547578
1 1      1995  3050.438507  6854.476008  5137.781659  1942.32987   5307.26172
1 1      1996  2769.73303   2259.820427  2902.868865  1545.236181  4141.737907
1 2      1994  15.21625969  1272.293423  1848.07715   1786.356259  14781.02941
1 2      1995  13.70839204  1186.898808  1798.366776  1774.197271  10048.62736
1 2      1996  12.44692726  1069.282104  1677.662829  1726.47415   7170.905624
| |      |
| |      | catch at age (from youngest to oldest)
| |      |
| |      | year
| fleet
integer specifying stock or sex
```

The lines for zone (sex) 1 must always precede those for zone (sex) 2, the lines for fleet  $i$  must always precede fleet  $i+1$ , and year  $y$  must always precede year  $y+1$ . Comments may only be inserted at the end of a line or the end of the file, after all data (as illustrated above). Every stock/fleet/year/age combination must have an entry associated with it (i.e., dummy values should be substituted for missing data). Note that in the present example there is one stock with two fleets covering three years (1994-1996).

In projections for which there is only one fleet, the catch at age may also be read from a binary direct access file with the same format as the abundance file discussed above.

## DISCARD FILE

This ASCII text file contains the estimates for the fraction of the total catch of each age class made by each fleet that is discarded dead (see discussion pertaining to equation 2.2). The data entries must be ordered by zone/sex, fleet and year as for the catch file discussed above. There is no provision for reading discards from direct access files.

## NATURAL MORTALITY RATE FILE

This file contains the estimates of natural mortality rate produced by the assessment model (assumed constant for all years). There are two file type options: an ASCII text file or a binary direct access file (such as produced by VPA-2BOX). The required format of the ASCII file is

```
1 0.2 0.2 0.3 0.3 0.3 0.3 0.3 0.2 0.2 0.1 0.1
2 11*0.2
| |
| natural mortality rate at age (from youngest to oldest)
integer specifying stock or sex
```

Note that, in the example, the entries for zone (sex) 2 are written in the shorthand notation 11\*0.2, which is equivalent to typing 0.2 eleven times.

The binary direct access file must have a record length of  $[4*(A-\alpha+1)*K]$ , where  $\alpha$  and  $A$  are the first and last age classes and  $K$  is the number of stocks/sexes. Each natural mortality value  $M$  should be stored as a 4-bit single precision variable written in the order  $((M(k,a), a=\alpha, A), k=1, K)$ .

## TRANSFER COEFFICIENT FILE

This file contains the estimates of the overlap or diffusion transfer coefficients. There are two file type options: an ASCII text file or a binary direct access file (such as produced by VPA-2BOX). The required formats are the same as for the natural mortality rate files discussed above.

## VULNERABILITY FILE

The entries in this ASCII file are interpreted as vulnerability coefficients if line 36 of the control file is negative. Otherwise, they are interpreted as the modifiers  $\lambda$  in the geometric mean calculations of equations (3.3) - (3.6). The required format is as follows:

```

1  1      0.0 0.1 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1  2      0.0 0.1 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
1  3      1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
2  1      11*1.0
2  2      11*1.0
|  |      |
|  |      | vulnerability modifiers from youngest age to oldest
| integer specifying fleet
integer specifying stock or sex

```

In this example there are two stocks (and two management zones), the first with three fleets and the second with two fleets. If the value of line 36 in the control file were positive, the coefficients would be interpreted as modifiers intending to represent regulations that eliminate the catch of the youngest animals and drastically reduce the fishing mortality rate on the next youngest age by fleets 1 and 2 in zone 1, but have no effect on fleet 3 in zone 1 or either of the two fleets in zone 2.



recruitment such that,  $\xi^2 = \log_e(CV^2 + 1)$ , where the  $CV$  is the coefficient of variation of recruitment on an arithmetic scale (typically a value on the order of 0.4). As discussed in connection with equations (2.21) and (2.22),  $\xi$  is estimated by its MLE. However, the value of  $\xi$  used for the stochastic projections is the larger of the estimate or the input value entered in the file. Note that, even if you chose to estimate the parameters  $\omega$  and  $\beta$  by setting the type to a positive integer, you may elect not to estimate  $\xi$  by entering a negative value (in which case the program will fix  $\xi$  to the absolute value of the input). At present there is no provision for estimating  $\rho$ ; the fitting procedure assumes  $\rho=0$  and the future projections will use the input value as given (so do not enter a negative value for  $\rho$  unless it truly is negative).

The last (seventh) entry is the value of the residual  $\eta$  used to initiate the autocorrelated error structure in the projections. This can have an important effect during the first few years of the projections, especially if the value of  $\rho$  is close to 1.0. Typically,  $\eta$  is set to the value estimated for the last year of the assessment model. However, if the historical recruitments during the most recent years are to be replaced via the algorithm discussed in connection with line 16 of the control file, then the value of  $\eta$  should be set to that for the most recent year where the recruitment is not being replaced (the program will update the annual values of  $\eta_y$  in addition to the recruitments). Inasmuch as the fitting procedure assumes  $\rho = 0$ , there is no provision for estimating  $\eta$ ; future projections will use the input value as given.

PRO-2BOX estimates the parameters of the spawner recruit curves from the historical recruitment and  $SSF$  observations unless instructed not to do so by entering a negative integer for the curve *type* (second entry in file). The following options are available:

- 1 Beverton and Holt curve estimated via equations (2.21) or (2.22).
- 2 Ricker curve estimated via equations (2.21) or (2.22).
- 3 two-line, linear regression with inflection at maximum observed  $SSF$ :

$$\beta = \max_{y=\psi}^{\Psi} SSF_y$$

$$\omega = \begin{cases} \beta \frac{\sum_{y=y_0}^Y N_{\alpha y} SSF_{y-\alpha}}{\sum_{y=y_0}^Y SSF_{y-\alpha}^2} & \text{additive} \\ \beta \frac{\sum_{y=y_0}^Y \frac{N_{\alpha y}}{SSF_{y-\alpha}}}{(Y - y_0 + 1)} & \text{multiplicative} \end{cases}$$

- 4 two-line, recruitment = geometric mean with inflection at minimum  $SSF$ :

$$\beta = \min_{y=\psi}^{\Psi} SSF_y$$

$$\omega = \exp \left\{ \frac{\sum_{y=y_0}^Y \log_e N_{\alpha y}}{(Y - y_0 + 1)} \right\}$$

- 5 two-line, recruitment as above with inflection at mean  $SSF$ :



$$\beta = \frac{\sum_{y=\psi}^{\Psi} SSF_y}{(\Psi - \psi + 1)}$$

- 6 constant recruitment at the arithmetic mean:

$$\omega = \sum_{y=y_0}^Y N_{\omega y} / (Y - y_0 + 1).$$

- 11 Beverton and Holt curve estimated as for option 1, but with an additional penalty restraining the predicted maximum recruitment from becoming too much larger than some reference point  $\tilde{\omega}$  as described in equation (2.23). The program will prompt the user to specify the range of years ( $Y_1$  and  $Y_2$ ) over which to compute the reference point from the observed recruitments. A negative value for  $Y_1$  will set the reference point equal to the largest value observed over the time period specified for the fitting. Positive inputs are interpreted as the years  $Y_1$  and  $Y_2$  for computing the reference point as an average of the corresponding observed recruitments.
- 12 Ricker curve estimated as for option 2, but with the additional penalty described above for option 11.

where  $y_0$  and  $Y$  are the first and last years defining the range of historical recruitments to use and  $\psi$  and  $\Psi$  are the first and last years defining the range of historical  $SSF$ 's (see control file line 41).

The binary direct access file must have a record length of  $[4*(5+n_y)*K]$ , where  $K$  is the number of stocks/sexes and  $n_y$  is the number of years of historical estimates. Each value should be stored as a 4-bit single precision variable written in the order,

$$\{ [type_k, \omega_k, \beta_k, \sigma_k, \rho_k, (\eta_{k,y}, y=1, n_y)], k=1, K \}.$$

# 4. OUTPUT FILES

Program PRO-2BOX writes a pair ASC-II files for each of a large number of output statistics (see Table 3). The file with the `.out` extension contains results from each individual bootstrap run. The file with the `.sta` extension provides a summary of the bootstrap results with the central tendencies and confidence limits.

**Table 3.** Output files produced by PRO-2BOX.

File name	Content	File types
BENCH- <i>k</i>	Benchmark statistics for stock/sex <i>k</i>	*.sta, *.out
BIO_f- <i>k</i>	Fishable biomass of stock/sex <i>k</i> ( $= \sum v_{ak} w_{ak} N_{ak}$ )	*.sta, *.out
BIO_t- <i>k</i>	Total biomass of stock/sex <i>k</i> ( $= \sum w_{ak} N_{ak}$ )	*.sta, *.out
Fapex- <i>k</i>	Apical fishing mortality rate	*.sta, *.out
Fcurr- <i>k</i>	Current (recent historical) fishing mortality rate	*.sta, *.out
RECRT- <i>k</i>	Number of age $\alpha$ recruits to stock/sex <i>k</i>	*.sta, *.out
SSBIO- <i>k</i>	Spawning stock biomass/fecundity ( <i>SSF</i> ) of stock/sex <i>k</i>	*.sta, *.out
SSBF01- <i>k</i>	<i>SSF</i> divided by equilibrium <i>SSF</i> associated with $F_{0.1}$	*.sta, *.out
SSBF20- <i>k</i>	<i>SSF</i> divided by equilibrium <i>SSF</i> associated with 20% SPR	*.sta, *.out
SSBF30- <i>k</i>	<i>SSF</i> divided by equilibrium <i>SSF</i> associated with 30% SPR	*.sta, *.out
SSBF40- <i>k</i>	<i>SSF</i> divided by equilibrium <i>SSF</i> associated with 40% SPR	*.sta, *.out
SSBMSY- <i>k</i>	<i>SSF</i> divided by equilibrium <i>SSF</i> associated with <i>MSY</i>	*.sta, *.out
SSNUM- <i>k</i>	Spawning stock abundance in numbers	*.sta, *.out
YIELD- <i>k</i>	Total landings in weight of zone/sex <i>k</i> (all fleets combined)	*.sta, *.out
SR-PARMS	Review of spawner-recruit parameters for both stocks	*.out

## \*.OUT FILES

The formats of the `.out` files generally follow the pattern

```

1  1  0.6042E+04 0.4958E+04 0.4051E+04 0.3268E+04 0.2628E+04 ...
|  |  |
|  |  | values for first historical year through last year of projection
|  |  | Bootstrap run identifier (0=deterministic value if input from VPA-2BOX)
Scenario identifier

```

There are three exceptions to this: SR-PARMS.OUT, Fcurr-\*.OUT and BENCH-\*.OUT (the \* referring to sex/stock 1 or 2).

*SR\_PARMS.OUT*

Contains the spawner-recruit curve parameters:

```

0 1 220000.00 16000.00 0.00 0.00 1 220000.00 16000.00 0.00 0.00
| | | | | | | | | | |
| | | | |  $\rho_1$  | | | | |  $\rho_2$ 
| | | | |  $\xi_1$  | | | | |  $\xi_2$ 
| | | | |  $\beta_1$  | | | | |  $\beta_2$ 
| |  $\omega_1$  | |  $\omega_2$ 
| Curve type stock 1 Curve type stock 2
Bootstrap run identifier

```

*Fcurr-\*.OUT*

Contains the calculated values of  $F_{current}$  for each fleet, i.e., the geometric mean of the historical fishing mortality rates discussed in connection with lines 22-24 of the quota file (option -999):

```

1 1 0.3107E+00 0.2015E+00 0.7111E+00
| | | | |
| | | values of  $F_{current}$  for each fleet
| Bootstrap run identifier (0=deterministic value if input from VPA-2BOX)
Scenario identifier

```

*BENCH-\*.OUT*

Contains the management benchmarks with labels:

RUN #	F MSY	MSY	Y/R MSY	S/R MSY	SPR MSY ...
0	0.5496E-01	0.7975E+06	0.3628E+04	0.9842E+05	0.3284E+00 ...
1	0.5222E-01	0.7899E+06	0.3141E+04	0.9123E+05	0.3784E+00 ...

The units for the yield (Y, MSY) and spawning stock biomass/fecundity (SSB) statistics are in thousand units. The per recruit statistics, Y/R and S/R, are in the units of the entries in the weight file and growth curves (see description under BENCH-\*.STA).

**\*.STA FILES**

The formats of the .sta files generally follow the pattern

SCENARIO	YEAR	LOWER CL	MEDIAN	UPPER CL	AVERAGE	RUN 0	STD. DEV.
1	1990	0.5578E+04	0.7325E+04	0.1051E+05	0.7221E+04	0.7508E+04	0.175EE+04
1	1991	0.4999E+04	0.7252E+04	0.1003E+05	0.7157E+04	0.7278E+04	0.2111E+04

Recall that run 0 should refer to the deterministic output and is not used in the calculations of the central tendencies or confidence limits. One line will be present for each scenario in the quotas

file and for each year (from the first year in the data to the last year in the projections).

There are two exceptions to the above format, *Fcurr-\*.STA* and *BENCH-\*.STA* (the \* referring to sex/stock 1 or 2):

*Fcurr-\*.STA*

Here fleet replaces year

SCENARIO	FLEET	LOWER CL	MEDIAN	UPPER CL	AVERAGE	RUN 0	STD. DEV.
1	1	0.5578E+00	0.7325E+00	0.1051E+01	0.7221E+00	0.7508E+00	0.1754E+00
1	2	0.4999E+00	0.7252E+00	0.1003E+01	0.7157E+00	0.7278E+00	0.2111E+00

*BENCH-\*.STA*

Contains the management benchmarks with labels:

MEASURE	LOWER CL	MEDIAN	UPPER CL	AVERAGE	RUN 0	STD. DEV.
F at MSY	0.798333E-01	0.895311E-01	0.100240E+00	0.900636E-01	0.906180E-01	0.756115E-02
MSY	0.278167E+08	0.325180E+08	0.378330E+08	0.326696E+08	0.323377E+08	0.400971E+07
Y/R at MSY	0.244992E+04	0.284631E+04	0.333458E+04	0.287157E+04	0.283985E+04	0.361840E+03
S/R at MSY	0.868601E+05	0.873252E+05	0.876734E+05	0.873004E+05	0.873294E+05	0.321760E+03
SPR AT MSY	0.341059E+00	0.342885E+00	0.344252E+00	0.342788E+00	0.342901E+00	0.126340E-02
SSB AT MSY	0.982537E+09	0.992908E+09	0.100486E+10	0.993629E+09	0.994430E+09	0.855859E+07
F at max. Y/R	0.798339E-01	0.895318E-01	0.100240E+00	0.900643E-01	0.906187E-01	0.756122E-02
Y/R maximum	0.244992E+04	0.284631E+04	0.333458E+04	0.287157E+04	0.283985E+04	0.361840E+03
S/R at Fmax	0.868593E+05	0.873245E+05	0.876727E+05	0.872998E+05	0.873288E+05	0.321773E+03
SPR at Fmax	0.341056E+00	0.342882E+00	0.344249E+00	0.342785E+00	0.342899E+00	0.126345E-02
SSB at Fmax	0.982530E+09	0.992899E+09	0.100485E+10	0.993621E+09	0.994422E+09	0.855769E+07
F 0.1	0.588339E-01	0.660424E-01	0.737450E-01	0.663493E-01	0.666187E-01	0.556437E-02
Y/R at F0.1	0.236117E+04	0.274173E+04	0.320839E+04	0.276552E+04	0.273355E+04	0.348624E+03
S/R at F0.1	0.113365E+06	0.114073E+06	0.114708E+06	0.114043E+06	0.114261E+06	0.513704E+03
SPR at F0.1	0.445130E+00	0.447909E+00	0.450403E+00	0.447793E+00	0.448650E+00	0.201707E-02
SSB at F0.1	0.128253E+10	0.129779E+10	0.131600E+10	0.129801E+10	0.130111E+10	0.122694E+08
F 20% SPR	0.125000E+00	0.140000E+00	0.156000E+00	0.140385E+00	0.141000E+00	0.114438E-01
Y/R at F20	0.223569E+04	0.258880E+04	0.301847E+04	0.260861E+04	0.258246E+04	0.324475E+03
S/R at F20	0.507243E+05	0.509596E+05	0.511563E+05	0.509476E+05	0.511057E+05	0.157404E+03
SSB at F20	0.572361E+09	0.580198E+09	0.586755E+09	0.579877E+09	0.581943E+09	0.583348E+07
F 30% SPR	0.910000E-01	0.102000E+00	0.113000E+00	0.102360E+00	0.103000E+00	0.828878E-02
Y/R at F30	0.243338E+04	0.282647E+04	0.330607E+04	0.285027E+04	0.281899E+04	0.358067E+03
S/R at F30	0.759402E+05	0.762469E+05	0.765786E+05	0.762560E+05	0.762937E+05	0.236839E+03
SSB at F30	0.856796E+09	0.867658E+09	0.878772E+09	0.867936E+09	0.868764E+09	0.867432E+07
F 40% SPR	0.680000E-01	0.760000E-01	0.850000E-01	0.765450E-01	0.770000E-01	0.612910E-02
Y/R at F40	0.242060E+04	0.281465E+04	0.330177E+04	0.284028E+04	0.280855E+04	0.359293E+03
S/R at F40	0.101096E+06	0.101478E+06	0.101990E+06	0.101520E+06	0.101601E+06	0.332848E+03
SSB at F40	0.114185E+10	0.115574E+10	0.117004E+10	0.115549E+10	0.115694E+10	0.114924E+08
F 90% max Y/R	0.468339E-01	0.525318E-01	0.584480E-01	0.527193E-01	0.526186E-01	0.441257E-02
Y 90% max Y/R	0.249352E+08	0.292102E+08	0.339933E+08	0.292913E+08	0.289028E+08	0.359558E+07
Y/R 90% max Y/R	0.219652E+04	0.255628E+04	0.299615E+04	0.257461E+04	0.253820E+04	0.324487E+03
S/R 90% max Y/R	0.132812E+06	0.133564E+06	0.134263E+06	0.133560E+06	0.134264E+06	0.583639E+03
SSB 90% max Y/R	0.150133E+10	0.151970E+10	0.154043E+10	0.152016E+10	0.152889E+10	0.144868E+08
F 75% of Fmax	0.598754E-01	0.671488E-01	0.751803E-01	0.675482E-01	0.679640E-01	0.567091E-02
Y 75% of Fmax	0.269014E+08	0.314486E+08	0.365821E+08	0.315931E+08	0.312718E+08	0.387478E+07
Y/R at 75% Fmax	0.236979E+04	0.275283E+04	0.322433E+04	0.277693E+04	0.274624E+04	0.349666E+03
S/R at 75% Fmax	0.111987E+06	0.112517E+06	0.112922E+06	0.112487E+06	0.112524E+06	0.371883E+03
SSB at 75% Fmax	0.126662E+10	0.127911E+10	0.129449E+10	0.128030E+10	0.128132E+10	0.110608E+08

Here F(label) refers to the apical fishing mortality rate corresponding to the various benchmark statistics discussed in chapter 2. The labels Y and MSY refer to the equilibrium yield in thousand units of weight (if the growth curve and input weights were expressed in kilograms, then the entries here would be read as metric tons). The label SSB is spawning stock fecundity (biomass), also in thousand units (a zero entry for SSB indicates that the corresponding level of F is not sustainable under the prescribed spawner-recruit relationship). The labels Y/R and S/R

refer to yield per recruit and spawning product (fecundity/biomass) per recruit, respectively, in the actual units of the growth/fecundity inputs (e.g., kilograms rather than metric tons), and SPR refers to the unit-less spawning potential ratio.

## 5. LITERATURE CITED

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# 6. APPENDICES

## APPENDIX 1. Sample control file with line numbers

```

      First column of file
Line |
  1  #*****
  2  #-----INPUT DATA FILE FOR PROGRAM PROJECT-----
  3  # Data entry is free-format. Null lines and comments must be
  4  # initiated here by pound signs (#) asterisks (*) or dashes (-). Do not,
  5  # however, interrupt a stream of vector inputs with a comment.
  6  #*****
  7  #
  8  #000000000000000000000000000000000000000000000000000000000000000000
  9  # Enter control information common to both zones/stocks/sexes below
 10  #000000000000000000000000000000000000000000000000000000000000000000
 11  1   Model type (1 = diffusion or no mixing, 2 = overlap, 3 = sex-specific)
 12  1   Number of sexes/stocks (enter 1 or 2)
 13  200 Number of bootstrap projections (enter 0 for deterministic only)
 14  80  Confidence interval in percent (e.g., 80)
 15 -911 Random number seed (should be a negative integer)
 16  3   Number of recruitments to replace with spawner-recruit curve
 17  1   Sex/stock to base Y/R stat's on (3=use both sexes/stocks combined)
 18  1   Sex to base S/R stat's on. Enter 1, 2 or 3(to use both sexes)
 19  1   Fraction of population belonging to sex 1 at age of recruitment
 20  1   Weight from growth curve for (0=all ages, 1=plus-group only, 2=none)
 21  #-----
 22  # First & last years in data file
 23  # |           |           | Last year in projections
 24  # |           |           |
 25  # 1975      1999      2040
 26  #-----
 27  # First age (same for both sexes/stocks)
 28  # |           | Last age (sex/stock 1)
 29  # |           |           | Last age for sex/stock 2 (unnecessary if 1 sex/stock)
 30  # |           |           |
 31  #  1          8          8
 32  #-----
 33  # Selectivity option: two positive integers indicate the first
 34  # and last years for a geometric mean of the F's at age. Negative entry
 35  # indicates user-specified vectors in the selectivity file are to be used
 36  1996 1998
 37  #-----
 38  # First & last years to use for recruitment calculations
 39  # |           |           | First & last years to use for spawning stock calc's. # |
 40  # |           |           |
 41  # 1976      1996      1991      1995
 42  #-----
 43  # Error type for recruitment projections and spawner-recruit curve fit
 44  2   (1=lognormal, 2=normal)
 45  #111111111111111111111111111111111111111111111111111111111111111111
 46  # Enter specific growth information for zone/stock 1
 47  #111111111111111111111111111111111111111111111111111111111111111111
 48  1   Number of distinct fleets
 49  11.80703 Average age of plus-group, negative=compute from growth curve
 50  0 0 0 0 0.5 1 1 1 1 1 Fraction mature (1 value for each age)
 51  #-----

```





## APPENDIX 2. Sample quota file with line numbers

```

=====
First column of file
Line |
1 #-----
2 # Enter the total number of projection scenarios
3 #-----
4 | 2
5 #-----
6 # SCENARIO 1 Current F in first year, followed by F fixed at 0.1 yr-1
7 #-----
8 # ***** CATCH LIMITS *****
9 # Sex or stock
10 # | fleet
11 # | | TAC for each projection year in thousand units
12 # | | |
13 | 1 1 100*100000000. {n*TAC is a convenient shorthand equivalent to typing the TAC n times}
14 | 1 2 100*100000000.
15 | 1 3 100*100000000.
16 | -1
17 # ***** F LIMITS *****
18 # Sex or stock
19 # | fleet
20 # | | F limit for each projection year in thousand units
21 # | | |
22 | 1 1 -9 100*0.1
23 | 1 2 -9 100*0.1
24 | 1 3 -9 100*0.1
25 | -1
26 #-----
27 # SCENARIO 2 TAC of 1000 mt
28 #-----
29 # ***** CATCH LIMITS *****
30 # Sex or stock
31 # | fleet
32 # | | TAC for each projection year in thousand units
33 # | | |
34 | 1 1 100*1000. {n*TAC is a convenient shorthand equivalent to writing the TAC n times}
35 | 1 2 100*1000.
36 | 1 3 100*1000.
37 | -1
38 # ***** F LIMITS *****
39 # Sex or stock
40 # | fleet
41 # | | F limit for each projection year in thousand units
42 # | | |
43 | 1 1 100*2
44 | 1 2 100*2
45 | 1 3 100*2
46 | -1

```

# 7. INDEX

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### **APPENDIX 3. WORKED EXAMPLE:**

See the User's Guide in **Appendix 2**.

### **APPENDIX 4. SOURCE CODE**

A copy of the entire source code has been filed with the ICCAT Secretariat and the full source code is available from the author ([Clay.Porch@noaa.gov](mailto:Clay.Porch@noaa.gov)) on request.