# I. Fundamentals

## Introduction

Sequential Population Analysis (SPA) is a family of methods for converting catch-at-age data into numbers-at-age. A common set of underlying ideas transcends methods having many versions and names. Virtual Population Analysis (VPA) (Fry, 1949, 1957) was the first configuration of these methods. Cohort analysis (Pope, 1972) is an approximate solution to VPA which has gained wide usage.

SPA is based on three concepts. The first is that of a *cohort*; a group of fish spawned in a single year. Cohorts may also be called year-classes. The second concept is that removals from the cohort are proportional to the cohort size and a rate coefficient. The proportionality is defined by the rate coefficient which is known as the *total mortality* and has two components the *natural mortality*, and the *fishing mortality*. Thus over a period of time the number of deaths, or removals from the cohort, depends upon how many animals were initially in the cohort and the instantaneous rate of total mortality. The third underlying concept is that the removals by fishing, i.e. the *catch*, C is proportional to *fishing intensity*, F, and the average number of animals in the population over the period of interest, $\overline{N}$ :

$$C = F\,\overline{N}$$

and is often known as Baranov's catch equation. Given two elements of this relationship the third is easily found. If the fishing mortality and numbers are known, the catch is predicted. If the C and F are known, the population size may be estimated, etc.

Unfortunately there is not enough information in the catch data usually available from the fishery to solve the catch equation for both numbers and fishing mortality. Additional information regarding the fishery, typically effort, catch rate or survey results, is needed. Incorporation of the additional information results in the need to 'tune' the analysis or to adopt statistical techniques. Many of the versions of SPA differ only in their method of tuning. The family of so called *ad hoc* methods reflects the subjective nature of the tuning process. The introduction of fixed tuning criteria (e.g. Laurec-Shepherd method) and statistical approaches (ADAPT) was made to remove this subjectivity.

This introduction to SPA proceeds from underlying principals of population dynamics. A consistent set of data are developed sequentially to display the basics of stock projection and SPA. As the purpose is tutorial, the examples are kept quite simple. The logical structure follows the removals from a cohort of fish from the age of entering the fishery through to the oldest age caught. Keeping track at each age of the removals, *numbers-at-age* and the survivors has two common uses in fishery science which are closely related: *yield-per-recruit* analysis and *stock projection*. Numbers-at-age are converted to *catches-at-age* and the analysis flows from youngest to oldest. It will then be shown that SPA progresses in the opposite direction. Catches are converted to numbers and the analysis goes from the oldest to the youngest in a cohort.

Two hypothetical data sets will be developed through this work. They are quite similar and based loosely on the Subdivision 4Vs and Division 4W cod stock. The first, simpler set is used to illustrate stock projection and introduces cohort analysis. The second set is used to demonstrate tuning of cohort analysis and ADAPT. Values in the various following tables have been computed to full precision and have been rounded for display. This may result in the appearance of small discrepancies when attempting to reproduce parts of calculations.

Before preceding with our development, some further vocabulary should be established. The youngest age at which fish are caught is known as the *recruitment age*. Fish at this age are called *recruits*. In general, fishing gear will be more efficient at catching fish at some ages than at others. This is known as the *selectivity of the gear* and may be considered to be either a function of age or size. For example age 3 fish may be one-tenth as likely to be retained in a certain mesh as a larger age 8 fish. In this case the selectivity would be 0.1 for age 3 compared to age 8. By tradition selectivities are normalized so that the largest value is one. The term *partial recruitment* is closely related to selectivity, and is often used interchangeably. The partial recruitment is the relative probability of being caught at age. It includes the selectivity of the gear, the distribution of the resource and fishery practices (e.g. targeting for a given age). Partial recruitments are also normalized so that the largest value is one. *Population size* may be described in terms of numbers of fish or biomass. *Biomass* is the numbers times an appropriate weight of an individual fish. If the biomass is multiplied by the partial recruitment, the result is known as the *fishable biomass*. Usually *catch* is defined in terms of numbers. If these numbers are multiplied by the appropriate weights the result is called *yield*, or less commonly *catch biomass*.

## Underlying Mathematics

The equation for removals from a cohort says that they are proportional to the numbers present and a removal rate which we call Z, the total (instantaneous) mortality. This represents a 'closed' stock. That is, there is no emigration or immigration and recruitment occurs only at one age. The relationship is intuitively reasonable. If there are more animals present for a given mortality rate, more will die. Similarly, for the same number of animals a higher mortality rate means more animals die over a given period. When rates are introduced the resultant equations must be handled with calculus. We will not deal with the details of the calculus; interested readers are referred to standard texts on population dynamics for details (Pielou, 1974; Ricklefs, 1979). Those who are not familiar with the technical aspects of calculus will have to accept without proof some unfamiliar assertions and techniques.

The basic equation for removals from a cohort is:

$$dN/dt = -Z\,N(t) \tag{1}$$

where the rate of removals from a group of animals is $dN/dt$, $Z$ is the instantaneous total mortality rate and $N(t)$ is the numbers at any time $t$. $Z$ has two components ($Z = F + M$); the fishing mortality, $F$ and natural mortality, $M$. The natural mortality is the composite of all deaths that are exclusive of catches. Mortality may thus include deaths caused by predation, disease, old age., etc. Typically $M$ is not known or even well estimated. The steps to solve Equation 1 may be found in any introductory calculus or population dynamics text and the result is

$$N(t) = N(0)\, e^{-Zt} \qquad (2)$$

where N(t) is the number surviving from an initial number alive at time zero, N(0), and $e^{-Zt}$ is the exponential function. This equation is known as exponential decay. For example if a population of 1 000 individuals had a total mortality rate of 0.3 per year, the number surviving and number dying over 4 years would be:

| Date | Number | Deaths |
|---|---|---|
| 1 Jan 1980 | 1 000 | 259 |
| 1 Jan 1981 | 741 | 192 |
| 1 Jan 1982 | 549 | 142 |
| 1 Jan 1983 | 407 | 106 |
| 1 Jan 1984 | 301 | |

The deaths for each year is the difference between the numbers alive on 1 January of that year and 1 January a year later. There is a fundamental difference in numbers and deaths. The numbers are those alive at a given instant, in this case 1 January each year, while the deaths are accumulated over a period, in this case a year. This distinction is important as we shall see in the catch equation and its applications.

## Catch Equation

The catch equation says that the catch over a period of time (C) is proportional to the intensity of fishing (F) and to the average number ($\overline{N}$), of fish available over that period:

$$C = F\, \overline{N} \qquad (3)$$

The numbers, N, are continuously changing over the fishing season as defined by exponential decay (Equation 2). In order to find the average abundance over a period from time 0 to time T we need to integrate the numbers (using calculus) and divide by the period:

$$\overline{N} = \left(\int N\, dt\right)/T \qquad (4)$$

After the bit of calculus, the answer is found to be:

$$\overline{N} = N(0)\,(1 - e^{-ZT})/ZT \qquad (5)$$

where the average number of fish is now equated to the number of fish at time zero. If we assume the interval T is one year and Z in an annual instantaneous rate, Equation 5 simplifies to:

$$\overline{N} = N(0)\,(1 - e^{-Z})/Z \qquad (6)$$

which may be substituted back into Equation 3 to give an expression for the annual catch:

$$C = N(0)\,(1 - e^{-Z})\,F/Z \qquad (7)$$

which is the familiar form of the catch equation. The right-hand side of Equation 7 has three components. The first is N(0) which is the number of fish at the beginning of the year. The second, $(1 - e^{-Z})$, is the fraction of those fish that will die during the year. The final factor is F/Z which is the proportion of deaths due to fishing. These three components together determines the catch. As was mentioned above, the N and the C are not conceptually the same. N is the number at an instant and C is the accumulation over the year.

## Projection of a Single Cohort

With the equations of the previous section, slightly altered to keep track of age, we can see how many would die and how many of those would be caught over a period of time. For example, we can start with a number of fish entering a fishery at say age 3 and follow them for say 7 years. Three items of information are needed; the natural mortality, the partial recruitment pattern and the weights-at- age.

We shall assume that the instantaneous annual natural mortality rate, M, is 0.2 for all ages. The partial recruitment (PR) and weights-at-age ($W_a$) are given in Table 1 and are based on patterns of Subdivision 4Vs and Division 4W cod (Halliday and White, 1989). Recruitment occurs at age 3.

TABLE 1. Summary of yield-per-recruit calculations with an F of 0.4.

| Age | $W_a$ | PR | $F_a$ | $Z_a$ | $e^{-Z_a}$ | $N_a$ | $B_a$ |
|---|---|---|---|---|---|---|---|
| 3 | .59 | 0.05 | .02 | .22 | .803 | 1 000 | 590 |
| 4 | .95 | 0.15 | .06 | .26 | .771 | 803 | 762 |
| 5 | 1.29 | 0.5 | .20 | .40 | .670 | 619 | 798 |
| 6 | 1.69 | 0.8 | .32 | .52 | .595 | 415 | 701 |
| 7 | 2.20 | 1.0 | .40 | .60 | .549 | 247 | 543 |
| 8 | 2.62 | 1.0 | .40 | .60 | .549 | 135 | 355 |
| 9 | 3.32 | 1.0 | .40 | .60 | .549 | 74 | 247 |
| Total | | | | | | 3 292 | 3 995 |

TABLE 1. Continued.

| Age | $N_a$ | $1\text{-}e^{-Z_a}$ | Deaths | $F_a/Z_a$ | $C_a$ | $Y_a$ |
|---|---|---|---|---|---|---|
| 3 | 1 000 | .197 | 197 | .091 | 18 | 11 |
| 4 | 803 | .229 | 184 | .231 | 42 | 40 |
| 5 | 619 | .330 | 204 | .500 | 102 | 132 |
| 6 | 415 | .405 | 168 | .615 | 103 | 175 |
| 7 | 247 | .451 | 111 | .667 | 74 | 163 |
| 8 | 135 | .451 | 61 | .667 | 41 | 107 |
| 9 | 74 | .451 | 34 | .667 | 22 | 74 |
| Total | | | | | 403 | 701 |

The first problem is then to determine the fishing mortality rates. Fishing mortality for an age group ($F_a$) is the product of the partial recruitment pattern and a fully recruited F (in this case 0.4), the F for those ages that have partial recruitment 1. For example, in Table 1 ages 7–9 are fully recruited. Because the fully recruited F is 0.4 the $F_a$ on these ages is 0.4. Age 5 has a partial recruitment of 0.5 which when multiplied by the fully recruited F results in an $F_a$ of 0.2 for this age. Similarly, fishing mortality at age for ages 3–9 are those seen in Column $F_a$ of Table 1. Often the term fully recruited is dropped and just F is used (somewhat ambiguously). These Fs may then be added to the natural mortality (0.2) to give the total mortality at age, Column $Z_a$. The next column is the fraction surviving and is $e^{-Z_a}$.

The numbers surviving from age a to age a+1 are found by multiplying by the exponential of the total mortality for that age:

$$N_{a+1} = N_a e^{-Z_a} \quad (8)$$

In our example, 1 000 recruits at age 3 would experience a total mortality of 0.22 which means 80.3% would survive. Note that although the total mortality is 0.22, 22% of the fish do not die, rather 19.7% die. The instantaneous rate should not be confused with the portion that die as the two are related by an exponential. The 803 fish age 4 fish would experience a total mortality of 0.26 because more are selected by the gear and 77.1% would survive to age 5, or 619 fish. This process is repeated until age 9 where only 74 fish remain from the initial 1 000 fish at age 3. The numbers-at-each age are multiplied by the weight-at-age ($N_a$) to give biomass-at-age ($B_a$). Although the numbers-at-age from this cohort decrease each year the biomass at age reaches a maximum of 798 kg at age 5. After that age the mortality rate exceeds the growth rate and the biomass of the cohort decreases. The upper portion of Table 1 shows the details of the determination of numbers-at-age and the corresponding biomass from the 1 000 recruits.

In the lower portion of Table 1, the fraction of the initial numbers that die at each age is given by $1\text{-}e^{-Z_a}$. The numbers that die at each age is then the product of the number entering an age and that fraction. The fraction of those deaths that are due to fishing at each age is $F_a/Z_a$ which when multiplied by the numbers dying gives the catch-at-age ($C_a$) (which is the Equation 7 we derived earlier).

$$C_a = N_a (1 - e^{-Z_a}) F_a/Z_a \qquad (9)$$

The catch (in numbers)-at-age is multiplied by the weight-at-age resulting in the yield-at-age ($Y_a$). Forty-two fish from the 1 000 recruits are expected to be caught at age 4 with a yield of 40 kg. The example shows that for 1 000 recruits, fishing with a fully recruited F of 0.4, this cohort should have a total yield of 701 kg through ages 3 to 9. For comparison, a similar calculation has been summarized in Table 2 with a fully recruited F of 0.8 instead of 0.4.

If the resultant numbers, catches etc. were divided by the number of recruits, the single cohort projection would be equivalent to Thompson-Bell yield-per-recruit (Thompson and Bell, 1934). In yield-per-recruit analysis, the yield resulting from a single recruit is calculated for various fully recruited Fs, partial recruitment patterns and perhaps M. The resulting patterns of yields are analyzed to determine target fishing mortalities. This analysis is essentially balancing of growth and mortality rates in light of some criterion, for example maximizing the yield-per-recruit.

TABLE 2. Projection of a single cohort with a fully recruited F of 0.8. The input weight-at-age and partial recruitment are the same as for the example in the text.

| Age | $W_a$ | PR | $Z_a$ | $e^{-Z_a}$ | $N_a$ | $B_a$ | Deaths | $C_a$ | $Y_a$ |
|---|---|---|---|---|---|---|---|---|---|
| 3 | .59 | 0.05 | .24 | .787 | 1 000 | 590 | 213 | 36 | 21 |
| 4 | .95 | 0.15 | .32 | .726 | 787 | 747 | 215 | 81 | 77 |
| 5 | 1.29 | 0.5 | .60 | .549 | 571 | 737 | 258 | 172 | 222 |
| 6 | 1.69 | 0.8 | .84 | .432 | 313 | 530 | 178 | 136 | 229 |
| 7 | 2.20 | 1.0 | 1.00 | .368 | 135 | 298 | 86 | 68 | 151 |
| 8 | 2.62 | 1.0 | 1.00 | .368 | 50 | 130 | 31 | 25 | 66 |
| 9 | 3.32 | 1.0 | 1.00 | .368 | 18 | 61 | 12 | 9 | 31 |
| Totals | | | | 2 875 | 3 093 | | 527 | 796 | |

## Stock Projection

For a stock projection, instead of dealing with a single cohort, the age distribution of the fish population of a standing stock is needed in advance. The standing stock is then aproportioned such that the age disaggregated population is described in a given year. In the single cohort example above, only the age of the fish was considered, not the year. However, here we need to recognize a cohort which recruits at age 3 in 1976 will be age 4 in 1977, etc. Thus the cohort proceed diagonally down to the right (the text table following Equation 12), using the cohort numbers from the above example), shows the standing stock in 1976 and the progression of the 1 000 recruits through the fishery. Again these are the numbers at a particular date, we have arbitrarily chosen 1 January. The standing stock in 1976 is 3 005 animals while the cohort that recruited in 1976 contributes 803 animals to the 1977 stock 619 to 1978, etc. This cohort is the 1975 year-class, because if they were aged 3 in 1978, they must have been born in 1975. The equation for survivorship now needs two subscripts, one for age (a) and one for the year (y):

$$N_{a+1,y+1} = N_{a,y}\, e^{-Z_{a,y}} \qquad (10)$$

The total mortality, $Z_{a,y,}$ is comprised of fishing and natural mortality, and the fishing mortality may be decomposed into an age effect (the partial recruitment, PR) and the annual series of fully recruited Fs:

$$Z_{a,y} = F_{a,y} + M_{a,y} \qquad (11)$$

and

$$F_{a,y} = PR_a \times F_y \qquad (12)$$

For convenience we have assumed that the natural mortality is the same value of 0.2 for all ages and years and thus the subscripts may be dropped from M.

| | No. of Recruits by Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| 3 | 1 000 | | | | | | | |
| 4 | 770 | 803 | | | | | | |
| 5 | 550 | | 619 | | | | | |
| 6 | 320 | | | 415 | | | | |
| 7 | 200 | | | | 247 | | | |
| 8 | 75 | | | | | 135 | | |
| 9 | 90 | | | | | | 74 | |
| Total | 3 005 | | | | | | | |

The standing stock 1976 may be aged ahead for the 4- through 9-year-olds in the same manner. When this is done a triangle of numbers-at-age and year are filled in. If the year subscript is added to Equation 9 the catch of each age for each year is found:

$$C_{a,y} = N_{a,y}\,(1 - e^{-Z_{a,y}})\, F_{a,y}/Z_{a,y} \qquad (13)$$

The corresponding triangle of numbers, catches-at-age and year is shown in Table 3.

TABLE 3. Projection of 1976 standing stock with a fully recruited F of 0.4

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 1000 | | | | | | | |
| 4 | 770 | 803 | | | | | | |
| 5 | 550 | 594 | 619 | | | | | |
| 6 | 320 | 369 | 398 | 415 | | | | |
| 7 | 200 | 190 | 219 | 237 | 247 | | | |
| 8 | 75 | 110 | 104 | 120 | 130 | 135 | | |
| 9 | 90 | 41 | 60 | 57 | 66 | 71 | 74 | |
| | | | | **Catch** | | | | |
| 3 | 18 | | | | | | | |
| 4 | 41 | 42 | | | | | | |
| 5 | 91 | 98 | 102 | | | | | |
| 6 | 80 | 92 | 99 | 103 | | | | |
| 7 | 60 | 57 | 66 | 71 | 74 | | | |
| 8 | 23 | 33 | 31 | 36 | 39 | 41 | | |
| 9 | 27 | 12 | 18 | 17 | 20 | 21 | 22 | |

In order to fill in the rest of the stock projection table, values must be supplied for the recruitment at age 3 for the years 1977 to 1983. We shall assume 1 000 recruits for each of these years except 1978 and 1979 which will have 2 000 recruits. Table 4 shows the numbers, catch and F for each age and year. The total biomass and yield for each year are also given.

In summary, to produce a stock projection one needs the standing stock at the beginning of the period of interest and values for recruits for each of the additional years of the projection. This represents the left-hand column and top row of our matrices which we will define as the "projection margin". Each age in the projection margin is then projected downward to the right until it reaches the oldest age or the last year of the projection. The partial recruitment pattern and the fully recruited F series determine the Fa,y. The last items of information required are the weights-at-age to determine yield and biomass and the natural mortality. In the projection, initial numbers, recruits and fishing mortalities are used to predict future numbers and catches. If the recruitment were constant year after year the standing stock would eventually have the same pattern as the cohorts. Some authors denote this equivalence as the “steady state”.

TABLE 4. Full matrix output for stock projection.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 1 000 | 1 000 | 2 000 | 2 000 | 1 000 | 1 000 | 1 000 | 1 000 |
| 4 | 770 | 803 | 803 | 1 605 | 1 605 | 803 | 803 | 803 |
| 5 | 550 | 594 | 619 | 619 | 1 238 | 1 238 | 619 | 619 |
| 6 | 320 | 369 | 398 | 415 | 415 | 830 | 830 | 415 |
| 7 | 200 | 190 | 219 | 237 | 247 | 247 | 493 | 493 |
| 8 | 75 | 110 | 104 | 120 | 130 | 135 | 135 | 271 |
| 9 | 90 | 41 | 60 | 57 | 66 | 71 | 74 | 74 |
| Total | 3 005 | 3 107 | 4 203 | 5 053 | 4 701 | 4 324 | 3 954 | 3 675 |
| Biomass | 3 507 | 3 584 | 4 369 | 5 230 | 5 514 | 5 485 | 5 239 | 4 892 |
| | | | | **Catch** | | | | |
| 3 | 18 | 18 | 36 | 36 | 18 | 18 | 18 | 18 |
| 4 | 41 | 42 | 42 | 85 | 85 | 42 | 42 | 42 |
| 5 | 91 | 98 | 102 | 102 | 204 | 204 | 102 | 102 |
| 6 | 80 | 92 | 99 | 103 | 103 | 207 | 207 | 103 |
| 7 | 60 | 57 | 66 | 71 | 74 | 74 | 148 | 148 |
| 8 | 23 | 33 | 31 | 36 | 39 | 41 | 41 | 81 |
| 9 | 27 | 12 | 18 | 17 | 20 | 21 | 22 | 22 |
| Total | 339 | 353 | 395 | 450 | 543 | 607 | 580 | 516 |
| Yield | 582 | 586 | 648 | 717 | 861 | 1 005 | 1 039 | 971 |
| | | | | **F** | | | | |
| 3 | .02 | .02 | .02 | .02 | .02 | .02 | .02 | .02 |
| 4 | .06 | .06 | .06 | .06 | .06 | .06 | .06 | .06 |
| 5 | .20 | .20 | .20 | .20 | .20 | .20 | .20 | .20 |
| 6 | .32 | .32 | .32 | .32 | .32 | .32 | .32 | .32 |
| 7 | .40 | .40 | .40 | .40 | .40 | .40 | .40 | .40 |
| 8 | .40 | .40 | .40 | .40 | .40 | .40 | .40 | .40 |
| 9 | .40 | .40 | .40 | .40 | .40 | .40 | .40 | .40 |

## Conversion of Catch to Numbers from a Single Cohort

We are now going to reverse the process. In the case of a single cohort, how can we estimate the numbers-at-age, and hence recruitment, from which the catch came? If the catch from the single cohort projection above is used, several methods may be employed. The simplest, and most conservative, is to accumulate the catch backwards down the cohort. We will use the cohort stated in Table 4. Using the same example we see that if 22 fish were caught at age 9, there must have been at least 22 alive on January 1 of the year they turned 9. If 41 were caught at age 8 from the same cohort, there must have been at least 63 (= 22 + 41) on 1 January of the year they turned 8. The second column of Table 5 shows the 41 caught as 8 year olds and the 22 caught the following year. The catch may be accumulated back down the cohort to get successive estimates of numbers of each younger age. The 3rd column of

Table 5 shows the results of catch accumulation. However, the estimate of the numbers recruited at age 3 is 402, which is not a very good approximation of the true value of 1 000.

TABLE 5. Estimates of numbers (N) and Fishing Mortality-at-age ($F_{est}$) from a single cohort catch-at-age.

| Age | Catch | Accumuative Catch | Corrected N | $Ce^M/2$ | Corrected C+N | Corrected Escape | $F_{est}$ |
|---|---|---|---|---|---|---|---|
| 9 | 22 | 22 | 22.0 | 24.3 | 24.3 | 73.1 | .400 |
| 8 | 41 | 63 | 67.9 | 45.3 | 75.0 | 134.6 | .410 |
| 7 | 74 | 137 | 156.9 | 81.8 | 173.4 | 246.2 | .404 |
| 6 | 103 | 240 | 294.6 | 113.8 | 325.6 | 414.6 | .321 |
| 5 | 102 | 342 | 461.9 | 112.7 | 510.4 | 619.1 | .201 |
| 4 | 42 | 384 | 606.1 | 46.4 | 669.9 | 802.6 | .060 |
| 3 | 18 | 402 | 758.3 | 19.9 | 838.1 | 1 000.2 | .020 |

The estimates may be improved by incorporating the "exponential survivorship" concept. If the 22 fish caught as 9-year-olds were all alive on 1 January of the year then they escaped the fishery as 8- year-olds and must have been alive on 1 January of the previous year. By inverting Equation 8 we can estimate the number of 8 year olds which survived to be 9, if there had been no fishery.

$$N_a = N_{a+1}\, e^{Z_a} \qquad (14)$$

In the absence of fishing $Z = M$ , then for ages 8 and 9 the equation becomes:

$$\begin{aligned} N_7 &= N_8\, e^M \qquad (15) \\ &= 22 \times 1.221 = 26.9 \end{aligned}$$

The estimated 26.9 which go on to age 9 may be added to the age 8 catch to yield an estimate of 67.9 animals on January 1 as age 8. Using this approximation for successive estimates to the previous age of the cohort, we have:

$$N_a = N_{a+1}\, e^M + C_a \qquad (16)$$

The numbers-at-age are corrected for the natural mortality between years. The column marked Corrected N in Table 5 contains the estimates from this procedure. Correcting for natural mortality significantly improves the estimate of the recruits. Once the procedure is initiated by setting the catch at the oldest to equal the numbers at the oldest age, steps backward down the cohort estimate the successive Ns with Equation 16.

The above conversion of catch over a year to numbers at the beginning of the year essentially assumes that all the catch took place on the first day. The estimates may be further improved by assuming that the catch took place at the middle of the year. This assumption requires a correction for the mortality over half the year. The contribution to the numbers in a year from the catch for that year is then $Ce^{M/2}$ and Equation 16 becomes:

$$N_a = N_{a+1}\, e^{M} + C_a\, e^{M/2} \qquad (17)$$

This is known as the cohort approximation (Pope, 1972). This equation is exact if the natural mortality is evenly distributed throughout the year and the fishery is a pulse fishery at mid-year. Now both the survivors ($N_{a+1}$) and the catch ($C_a$) are corrected for natural mortality. The 6th column of Table 5 (Corrected C + N) shows the resultant numbers-at-age estimated by this formula. It is seen to provide about a 10% improvement over the previous method. As above, the process is started by converting the catch in the oldest age into numbers that must have been there at the first of the year to support the catch:

$$N_9 = C_9\, e^{M/2} \qquad (18)$$

Equation 17 allows to step backwards down the cohort, once an estimate of N at the oldest age is completed. Equation 18 assumes that all the animals in the oldest age on 1 January are caught on 1 June. But such a removal rate presumes that the fishing mortality is infinite, i.e. all the fish alive were caught. If some fish escape the fishery a further correction is required. One way to do that would be to assume a level of escapement as estimated at $N_{10}$. Then Equation 17 can be used to fill in all the Ns from age 9 to 3. However, the more common practice is to assume a fishing mortality for the oldest age and once the F and the C in the oldest age are known, the catch equation can be solved for N. If A is the oldest age, then rearranging Equation 9 gives:

$$N_A = C_A Z_A / F_A\,(1 - e^{-Z_A}) \qquad (19)$$

If we assume that F is 0.4 for age 9 (which is the true value) then $N_9$ is estimated at 73.1 fish. The cohort equation is then used to step back through the catches at age and the resulting numbers closely approximate the true values. These values are given in the column "Corrected

Escape" in Table 5. Once the numbers-at-age have been estimated, the fishing mortality at age can be derived by rearranging Equation 8.

$$N_{a+1} = N_a e^{-Z_a} = N_a e^{-(F_a+M)} \quad (8)$$

$$N_{a+1}/N_a = e^{-(F_a+M)}$$

$$\ln(N_{a+1}/N_a) = -F_a - M$$

$$F_a = -\ln(N_{a+1}/N_a) - M \quad (20)$$

where ln denotes the natural logarithm. The estimates for ages 8 through 3 for the single cohort are given in Table 5 (column $F_{est}$). Recall that the value for the oldest age is assumed and not estimated by Equation 20.

# II. Simple Cohort Analysis

## Introduction

In the same manner by which the single cohort projection was generalized into a stock projection by adding a subscript for time, the single cohort can be expanded to include time. The equation used to step backwards down a cohort (Equation 17) becomes:

$$N_{a,y} = N_{a+1,y+1}\, e^{M} + C_{a,y}e^{M/2} \qquad (21)$$

and the equation for starting the process at the oldest age A:

$$N_{A,y} = C_{A,y}Z_{A,y}/F_{A,y}\,(1 - e^{-Z_{A,y}}) \qquad (22)$$

If the catch data by age and year are displayed in the standard layout with the ages in rows and columns for years, the bottom row will be the oldest age for, and require the use of, Equation 22 for each year. In the most recent year the oldest age in each cohort will be the same as the fish age, and again Equation 22 will have to be used for each age (except the oldest which is in the bottom row).

For convenience let us define the "cohort margin" as the bottom row and right-hand column of an age by year matrix. (Table 6). This margin of the numbers-at-age matrix must first be filled. It may be filled by assuming the values or they may be derived iteratively. The concept behind an iterative filling of the F for the oldest ages will be given in the following section. Then Equation 22 can be applied and once applied, each cohort's catch is converted to numbers by Equation 21 and the entire numbers-at-age and year matrix is obtained from catch-at-age and year matrix. The F at age and year is determined in a similar manner. The values in the cohort margin are assumed and all the others are found by an equation analogous to Equation 20:

$$F_{a,y} = -\ln(N_{a+1,y+1}/N_{a,y}) - M \qquad (23)$$

For illustration we will begin the process by assuming that the F in the oldest age for each year is 0.5, even though we know the correct fully recruited F is 0.4. Assuming this F gives a factor of 2.78 for converting the catch-at-age 9 into numbers using Equation 22.

$$N_{9,y} = C_{9,y} Z_{A,y} / F_{A,y} (1 - e^{-Z_{A,y}})$$

$$N_{9,y} = C_{9,y}\, 0.7/0.5\, (1 - e^{-0.7})$$

$$N_{9,y} = 2.78\ C_{9,y}$$

Table 6 shows the oldest age portion of the cohort margin which has been using this factor and then Equation 21 to fill back down the cohorts. Because the estimate of the terminal F is too high, 0.5 instead of 0.4, the numbers-at-age in Table 6 are too small.

TABLE 6. Cohort estimates from catch in Table 4. The fishing mortality (F) on the oldest age is set at 0.5.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 960 | 960 | | | | | | |
| 4 | 738 | 770 | 770 | | | | | |
| 5 | 530 | 568 | 592 | 592 | | | | |
| 6 | 303 | 351 | 376 | 393 | 393 | | | |
| 7 | 186 | 175 | 205 | 218 | 228 | 228 | | |
| 8 | 66 | 98 | 92 | 108 | 114 | 120 | 120 | |
| 9 | 75 | 33 | 50 | 47 | 56 | 58 | 61 | 61 |
| | | | | **F** | | | | |
| 3 | .021 | .021 | | | | | | |
| 4 | .063 | .062 | .062 | | | | | |
| 5 | .210 | .212 | .211 | .211 | | | | |
| 6 | .346 | .341 | .344 | .342 | .342 | | | |
| 7 | .442 | .445 | .441 | .446 | .443 | .443 | | |
| 8 | .485 | .468 | .466 | .461 | .473 | .474 | .474 | |
| 9 | .500 | .500 | .500 | .500 | .500 | .500 | .500 | .500 |

The remainder of the cohort margin, the numbers in the last year, are filled in a similar fashion. We assume the same fully recruited F of 0.5 which is multiplied by the partial recruitment pattern we used above (0.05, 0.15, 0.5, 0.8, 1.0, 1.0, 1.0). See the rightmost column under F in Table 7.

In general of course this pattern would not be known and would have to be estimated or assumed. Equation 22 is used to convert each of the catches from last year into Ns and the cohort equation is used to fill back in as is seen in Table 7. The oldest age in the most recent year has been done twice, once with the oldest ages in Table 6 and again now as the most recent years in Table 7. It is of course unnecessary to estimate this cohort twice. Tables 6 and 7 may be combined to give a complete cohort analysis of the numbers and F at age and year from the catch data. The combined tables are given in Table 8 which may be compared to the true values in Table 4.

TABLE 7. Cohort estimates from catch in Table 4. The fully recruited fishing mortality (F) on the most recent year is set at 0.5 and the partial recruitment is the true value from Table 4.

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Numbers** | | | | |
| 3 | | 960 | 1 884 | 1 824 | 869 | 832 | 802 | 804 |
| 4 | | | 770 | 1 510 | 1 461 | 695 | 665 | 641 |
| 5 | | | | 592 | 1 159 | 1 119 | 531 | 507 |
| 6 | | | | | 393 | 765 | 731 | 342 |
| 7 | | | | | | 228 | 439 | 412 |
| 8 | | | | | | | 120 | 225 |
| 9 | | | | | | | | 61 |
| | | | | **F** | | | | |
| 3 | | .02 | .02 | .02 | .02 | .02 | .03 | .03 |
| 4 | | | .06 | .06 | .07 | .07 | .07 | .08 |
| 5 | | | | .21 | .22 | .23 | .24 | .25 |
| 6 | | | | | .34 | .36 | .38 | .40 |
| 7 | | | | | | .44 | .47 | .50 |
| 8 | | | | | | | .47 | .50 |
| 9 | | | | | | | | .50 |

TABLE 8. Catch data and cohort estimates from Table 4. The fully recruited fishing mortality (F) on the most recent year is set at 0.5 and the partial recruitment is the true value from Table 4.

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Catch** | | | | |
| 3 | 18 | 18 | 36 | 36 | 18 | 18 | 18 | 18 |
| 4 | 41 | 42 | 42 | 85 | 85 | 42 | 42 | 42 |
| 5 | 91 | 98 | 102 | 102 | 204 | 204 | 102 | 102 |
| 6 | 80 | 92 | 99 | 103 | 103 | 207 | 207 | 103 |
| 7 | 60 | 57 | 66 | 71 | 74 | 74 | 148 | 148 |
| 8 | 23 | 33 | 31 | 36 | 39 | 41 | 41 | 81 |
| 9 | 27 | 12 | 18 | 17 | 20 | 21 | 22 | 22 |
| | | | | **Numbers** | | | | |
| 3 | 960 | 960 | 1 884 | 1 824 | 869 | 832 | 802 | 804 |
| 4 | 738 | 770 | 770 | 1 510 | 1 461 | 695 | 665 | 641 |
| 5 | 530 | 568 | 592 | 592 | 1 159 | 1 119 | 531 | 507 |
| 6 | 303 | 351 | 376 | 393 | 393 | 765 | 731 | 342 |
| 7 | 186 | 175 | 205 | 218 | 228 | 228 | 439 | 412 |
| 8 | 66 | 98 | 92 | 108 | 114 | 120 | 120 | 225 |
| 9 | 75 | 33 | 50 | 47 | 56 | 58 | 61 | 61 |
| | | | | **F** | | | | |
| 3 | .02 | .02 | .02 | .02 | .02 | .02 | .03 | .03 |
| 4 | .06 | .06 | .06 | .06 | .07 | .07 | .07 | .08 |
| 5 | .21 | .21 | .21 | .21 | .22 | .23 | .24 | .25 |
| 6 | .35 | .34 | .34 | .34 | .34 | .36 | .38 | .40 |
| 7 | .44 | .45 | .44 | .45 | .44 | .44 | .47 | .50 |
| 8 | .48 | .47 | .47 | .46 | .47 | .47 | .47 | .50 |
| 9 | .50 | .50 | .50 | .50 | .50 | .50 | .50 | .50 |

## *Ad hoc* Tuning of Cohort Analysis

The previous section showed that if we can provide F values for the cohort margin, the rest of the numbers and F matrices can be filled in a stepwise manner. The problem is how to come up with appropriate values to start the process. Such a procedure is called tuning. It is done by comparing the output of the cohort analysis with additional information. For example, cohort analysis produces numbers-at-age which can be converted into a biomass time series by multiplying by the weight-at-age. The resultant biomasses can be compared to biomass from a research survey or to the catch rate from the fishery. Catch rates are catch in weight-per-unit-effort, e.g. tons per hour fishing. The F table from cohort analysis can be converted into a times series by taking the average F or the fully recruited F for each year. The resultant F time series can be compared to the effort expended by the fleet. To formalize these arguments, assume that the fully recruited fishing mortality is comprised of two components, the efficiency of the gear (q) and the amount of effort (E).

$$F = q\,E \qquad (24)$$

The relationship is consistent with intuition, if one fishes harder (more effort) the mortality rate will be higher and if one uses a more efficient gear at the same level of effort the mortality will be higher. If this is substituted into the catch equation (Equation 3) we find:

$$C = q\,E\,\overline{N} \qquad (25)$$

If Equation 25 is multiplied by weight, the catch is converted to yield, Y, and the numbers to biomass, B:

$$Y = q\,E\,\overline{B} \qquad (26)$$

which when divided by effort states that the catch rate (yield per unit effort) should be proportional to the average biomass:

$$CPUE = Y/E = q\,\overline{B} \qquad (27)$$

The catch rate or catch-per-unit-effort is often abbreviated as CPUE. This same relationship can be used to include data from research surveys. The surveys use a standard effort unit; in Canada the standard is a tow duration of half an hour with a specified trawl. With a constant effort the catch and catch rate are proportional. The survey index of abundance is equivalent to a catch rate from a fleet which expends very little effort. Surveys also occur over a fairly brief period of time, say a few weeks, which means that the average biomass in Equation 27 is very close to the actual instantaneous biomass, B(t).

To illustrate the tuning process another stock projection using the same standing stock in 1976 and same recruitment series and partial recruitment as in the stock projection above is performed. But instead of a constant fully recruited F in all years we will use the values shown in the bottom row of the F portion of Table 9. The more complicated fully recruited F series makes the data more realistic and is necessary for tuning.

TABLE 9. Projection to generate catch data to illustrate *ad hoc* and ADAPT tuning.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 1 000 | 1 000 | 2 000 | 2 000 | 1 000 | 1 000 | 1 000 | 1 000 |
| 4 | 770 | 803 | 807 | 1 613 | 1 605 | 803 | 799 | 799 |
| 5 | 550 | 594 | 628 | 631 | 1 244 | 1 238 | 610 | 607 |
| 6 | 320 | 369 | 418 | 443 | 423 | 834 | 789 | 389 |
| 7 | 200 | 190 | 237 | 269 | 263 | 252 | 458 | 433 |
| 8 | 75 | 110 | 115 | 144 | 148 | 144 | 125 | 227 |
| 9 | 90 | 41 | 67 | 70 | 79 | 81 | 72 | 62 |
| | | | | **Catch** | | | | |
| 3 | 18 | 13 | 27 | 36 | 18 | 22 | 22 | 27 |
| 4 | 41 | 32 | 32 | 85 | 85 | 53 | 52 | 62 |
| 5 | 91 | 75 | 79 | 104 | 205 | 249 | 123 | 143 |
| 6 | 80 | 72 | 81 | 110 | 106 | 251 | 237 | 135 |
| 7 | 60 | 45 | 56 | 81 | 79 | 90 | 165 | 179 |
| 8 | 23 | 26 | 27 | 43 | 44 | 52 | 45 | 94 |
| 9 | 27 | 10 | 16 | 21 | 24 | 29 | 26 | 26 |
| | | | | **F** | | | | |
| 3 | .020 | .015 | .015 | .020 | .020 | .025 | .025 | .030 |
| 4 | .060 | .045 | .045 | .060 | .060 | .075 | .075 | .090 |
| 5 | .200 | .150 | .150 | .200 | .200 | .250 | .250 | .300 |
| 6 | .320 | .240 | .240 | .320 | .320 | .400 | .400 | .480 |
| 7 | .400 | .300 | .300 | .400 | .400 | .500 | .500 | .600 |
| 8 | .400 | .300 | .300 | .400 | .400 | .500 | .500 | .600 |
| 9 | .400 | .300 | .300 | .400 | .400 | .500 | .500 | .600 |

Additional information to the catch-at-age is needed for the tuning process. The following text table contains effort, survey index and CPUE, to aid in tuning the cohort analysis of catch data from Table 8.

Additional annual data used to illustrate tuning:

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| Effort | 193.2 | 124.0 | 120.7 | 178.6 | 159.1 | 196.8 | 201.8 | 227.7 |
| Survey | 266.7 | 251.6 | 302.3 | 349.1 | 414.7 | 449.6 | 365.6 | 361.6 |
| CPUE | 3.01 | 3.67 | 4.42 | 4.39 | 5.68 | 6.30 | 5.89 | 5.33 |

The effort data were derived from the true F by dividing it by an efficiency of 0.0025 and then adding a small amount of random noise. The survey series is similarly derived from the true biomass series by multiplying by a survey efficiency at age of 0.02, 0.06, 0.08 for ages 3 to 5 and 0.1 for ages 6 to 9, and then adding a small amount of random noise; lognormal noise with a coefficient of variation of 10% was added to the survey biomass at age and effort series. The CPUE is found by multiplying the catch in Table 9 by the weights-at-age to give the catch in terms of weights and then dividing by the effort series.

The cohort analysis proceeds as above using Equations 21 and 22. A fully recruited F of 0.5 was assumed for all years. Biomass and fishable biomass are estimated from the numbers-at-age in Table 10 as well as the average F, the average F is a simple unweighted F, but some authors have advocated weighting the F by the catch or numbers-at-age. The resultant series are given in Table 11.

TABLE 10. Cohort analysis of catch data from Table 9 using terminal fully recruited fishing mortality (F) of 0.5.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 1 005 | 1 037 | 2 102 | 2 150 | 1 113 | 1 157 | 1 187 | 1 197 |
| 4 | 774 | 807 | 836 | 1697 | 1 728 | 895 | 927 | 951 |
| 5 | 524 | 596 | 632 | 656 | 1 312 | 1 338 | 685 | 711 |
| 6 | 300 | 347 | 420 | 445 | 443 | 889 | 870 | 450 |
| 7 | 167 | 174 | 219 | 271 | 265 | 267 | 501 | 497 |
| 8 | 58 | 82 | 102 | 129 | 148 | 145 | 137 | 261 |
| 9 | 75 | 27 | 44 | 59 | 66 | 81 | 72 | 71 |
| | | | | **F** | | | | |
| 3 | .020 | .014 | .014 | .019 | .018 | .022 | .021 | .025 |
| 4 | .060 | .045 | .043 | .057 | .056 | .067 | .064 | .075 |
| 5 | .212 | .150 | .150 | .193 | .190 | .230 | .221 | .250 |
| 6 | .348 | .259 | .240 | .320 | .306 | .374 | .359 | .400 |
| 7 | .509 | .336 | .332 | .402 | .401 | .469 | .451 | .500 |
| 8 | .563 | .429 | .351 | .466 | .403 | .504 | .451 | .500 |
| 9 | .500 | .500 | .500 | .500 | .500 | .500 | .500 | .500 |

Table 11. Estimates of times series for tuning from results in Table 10.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| Average F | .316 | .248 | .233 | .279 | .268 | .309 | .295 | .321 |
| Total Biomass | 3 279 | 3 420 | 4 453 | 5 605 | 5 928 | 5 996 | 5 632 | 5 302 |
| Fishable Biomass | 1 652 | 1 685 | 2 050 | 2 456 | 2 913 | 3 462 | 3 482 | 3 252 |

The correlation coefficients between these three series and the additional information in the above text table are: Average F *versus* effort, 0.96; total biomass *versus* survey index, 0.93; and fishable biomass *versus* CPUE, 0.95. Similarly, trial values for fully recruited Fs could be generated for a range say from 0.1 to 1.0 in steps of 0.1. The correlation coefficients for this range of Fs for each of the three regressions are given in Table 12. The biomass *versus* survey series peaks at an F of 0.5 The fishable biomass *versus* CPUE suggests that the terminal F should be 0.7 or larger. Finally, the average F *versus* effort peaks at 0.6. Because of the added noise these indices are not consistent. However, the best guess is that the true terminal F would be in the vicinity of 0.6, which is indeed the true value. When more than one index is available for tuning, it may be desirable to combine them into a single index with some weighting procedure. As will be described below, the Laurec-Shepherd method does this automatically and it is also possible within ADAPT.

TABLE 12. Regression coefficients for *ad hoc* tuning.

| Trial F | .100 | .200 | .300 | .400 | .500 | .600 | .700 | .800 | .900 | 1.000 |
|---|---|---|---|---|---|---|---|---|---|---|
| Biom *vs* Survey | .716 | .800 | .871 | .919 | .935 | .921 | .886 | .841 | .793 | .746 |
| FBiom *vs* CPUE | .745 | .817 | .877 | .922 | .951 | .967 | .972 | .969 | .960 | .948 |
| Ave F *vs* Effort | .006 | .295 | .619 | .856 | .957 | .972 | .954 | .927 | .899 | .874 |

## Partial Recruitment and Oldest Age F Patterns

As the catch is accumulated into numbers-at-age backwards down the cohort, the estimates of F get better (if the natural mortality is correct). This convergence towards the true values was noted by Pope (1972), and the F portion of Table 10 shows this phenomenon. The age 9 Fs are all estimated at 0.5 instead of the true values given in Table 9. But, the values at age 7 begin to show some of the true underlying pattern. If the cohort analysis was re-run with the fully recruited F of 0.6, estimated from the tuning and the pattern from age 7 substituted for age 9, we would find a better approximation to the true pattern. Our example had the correct partial recruitment but of course this would not generally be available. One would then use an analogous approach for estimating the partial recruitment pattern. By looking at the Fs at age for say the 1981 and 1982, an estimate of the partial recruitment would be found that would be used for the next cohort run.

Substituting patterns from younger ages for the year to year F pattern and earlier years for the partial recruitment is done until the procedure converges. Table 13 contains the second iteration in such a sequence. Note for example the improvement in the estimated number of 3 year olds. There are a number of schemes used to improve the convergence of the pattern determination. One is averaging over a number of years or ages. Some authors advocate weighting the averages with the numbers-at-age estimates, but most prefer to use simple averages. The results in Table 13 are better than one can expect in practice. The data are less noisy and better behaved, and we have used the true partial recruitment pattern which would not be known. A number of *ad hoc* methods are reviewed in (Mohn, 1983) as well as a comparison of their performance and recommendations.

TABLE 13. Second iteration of cohort analysis to improve F estimates in the most recent year and the oldest age.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 1 025 | 1 006 | 2 010 | 2 007 | 1 001 | 1 000 | 1 000 | 1 000 |
| 4 | 785 | 823 | 811 | 1 621 | 1 610 | 804 | 799 | 798 |
| 5 | 552 | 606 | 645 | 635 | 1 250 | 1 242 | 610 | 607 |
| 6 | 321 | 370 | 428 | 456 | 426 | 838 | 791 | 389 |
| 7 | 192 | 190 | 238 | 277 | 274 | 253 | 459 | 433 |
| 8 | 71 | 103 | 115 | 144 | 153 | 152 | 125 | 227 |
| 9 | 74 | 37 | 61 | 70 | 79 | 85 | 78 | 62 |
| | | | | **F** | | | | |
| 3 | .020 | .015 | .015 | .020 | .020 | .025 | .025 | .030 |
| 4 | .059 | .044 | .045 | .060 | .060 | .075 | .075 | .090 |
| 5 | .200 | .147 | .146 | .200 | .200 | .251 | .251 | .300 |
| 6 | .322 | .241 | .235 | .311 | .320 | .401 | .403 | .480 |
| 7 | .424 | .302 | .302 | .391 | .385 | .502 | .504 | .600 |
| 8 | .436 | .325 | .303 | .404 | .387 | .473 | .504 | .600 |
| 9 | .509 | .336 | .332 | .402 | .401 | .469 | .451 | .600 |

# III. ICES Tuning Methods

## Introduction

So called "tuning methods" began to be developed in ICES during the 1980s, mainly by the Roundfish Working Group. At that time the main source of data other than commercial catch-at-age data was commercial effort data. In contrast to the situation in Canada, data from research vessel surveys were restricted to indices of abundance of the recruiting year-classes, making this source of information of little value in calibrating VPA. Because effort data were the principal source of additional information, tuning methods concentrated on ways of utilising them in the most appropriate way. It was believed, probably correctly, that the catchability of commercial effort changed with time and this led people to try and account for trends in the data due to an increase in vessel fishing power. This was done by examining estimates of catchability and much of the elements of the approach was incorporated into "catchability analysis" which later formed the basis of the most commonly used method, the "Laurec-Shepherd method".

## Catchability Tuning

The easiest way to understand tuning using catchability is to go through the process step by step. First let us assume that we have chosen some initial values of fishing mortality, F, on the oldest age (7 in this case). This enables us to calculate the Fs in the next youngest age group using the usual VPA equations. Thus for a data set of 7 age groups and 6 years we would have;

| | Year | | | | | |
|---|---|---|---|---|---|---|
| Age | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 |
| 6 | $F_{6,80}$ | $F_{6,81}$ | $F_{6,82}$ | $F_{6,83}$ | $F_{6,84}$ | |
| 7 | $F_{7,80}$ | $F_{7,81}$ | $F_{7,82}$ | $F_{7,83}$ | $F_{7,84}$ | $F_{7,85}$ |
| Effort | $E_{80}$ | $E_{81}$ | $E_{82}$ | $E_{83}$ | $E_{84}$ | $E_{85}$ |

The table also gives fishing effort. We can assume in this example that the effort data account for all the fishing mortality, i.e. that one fleet s responsible for all the catch. To obtain catchability, q, we simply divide the fishing mortality, F, by effort, E in each year and age. Thus for age 6 in 1980, for example, we get;

$$q_{6,80} = F_{6,80} / E_{80} \tag{28}$$

We can now write;

| | Year | | | | | |
|---|---|---|---|---|---|---|
| Age | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 |
| 6 | $q_{6,80}$ | $q_{6,81}$ | $q_{6,82}$ | $q_{6,83}$ | $q_{6,84}$ | |

The problem now is to estimate $F_{6,85}$. A simple procedure is to assume that q is constant for each year and that any observed variablity in the annual estimates is just noise. If this is so then simply taking an average of the calculated qs will give an estimate of $q_{6,85}$. Thus we can calculate;

$$q_{6,85} = \frac{1}{5}(q_{6,80}+q_{6,86}+q_{6,82}+q_{6,83}+q_{6,84}) \quad (29)$$

Now if we want to estimate $F_{6,85}$ all we have to do is multiply the catchability by the effort in 1985, i.e.;

$$F_{6,85} = q_{6,85}\ E_{85} \quad (30)$$

Having calculated an F for age 6 in 1985 it is now possible to run the VPA back to the next age group. Using the same procedure we can calculate $F_{5,85}$ and fill out another row on the F-at-age table;

| | Year | | | | | |
|---|---|---|---|---|---|---|
| Age | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 |
| 5 | $F_{5,80}$ | $F_{5,81}$ | $F_{5,82}$ | $F_{5,83}$ | $F_{5,84}$ | |
| 6 | $F_{6,80}$ | $F_{6,81}$ | $F_{6,82}$ | $F_{6,83}$ | $F_{6,84}$ | $F_{6,85}$ |
| 7 | $F_{7,80}$ | $F_{7,81}$ | $F_{7,82}$ | $F_{7,83}$ | $F_{7,84}$ | $F_{7,85}$ |

This process can be repeated for all age groups (except the oldest) to obtain estimates of F and population sizes.

When catchability tuning was first developed it was assumed that there were trends in q with time. Rather than take an average q, to obtain a revised input F, q was plotted against time and attempts were made to fit trends to the data. These were usually linear, and the trend was then extrapolated to obtain q for the most recent year. However, subsequent work showed that fitting trends was a rather dangerous procedure even if there were real trends in the data. This was because there is frequently insufficient information in the data to estimate the trends adequately and there is a danger of introducing trends into the VPA which are not really there at all. This can have serious consequences for the assessment.

## Laurec-Shepherd Tuning

It is not difficult to see that underlying the tuning procedure described above is the assumption that fishing mortality, F, is a linear function of effort, i.e.:

$$F = q\ E \tag{31}$$

In fact it is often difficult to detect simple linear relationships of this type from real data and catchability analysis tried to find the best ways of estimating q in the input year. If F and E are the fishing mortality and effort in the input year, and q is a vector of observed catchabilities then we can summarise the tuning problem as:

$$F = g(q)\ E \tag{32}$$

where g is a function which relates q in the input year to the historical observations. The problem is to find the most appropriate function, g, for the fishery data concerned. In the case of the Laurec-Shepherd method it is assumed that q at any age is constant with time and that the variability in the observed qs is due to log normal errors. Thus if Q is the log of q then:

$$Q' = Q + \varepsilon \text{ where } \varepsilon \sim N(O, \sigma^2) \tag{33}$$

where Q' is the observed value of log(q). If this is the case then the best estimate of q in the input year is the geometric mean of the observed qs, i.e.;

$$g(q) = \exp(\overline{Q}) \tag{34}$$

It is then simple to calculate F. It is important to realise at this point that because of the assumptions made in the calculation of Q it is possible to calculate the variance, $\sigma^2$, and hence a variance of the estimate of F. The usefullness of this will become clear below.

So far all the descriptions of the methods have assumed that the fishing mortality is generated from a single fleet for which the fishing effort is known. In practice effort is usually known for only some of the fleets exploiting a stock. It is not difficult, however, to modify the approach to account for this. Calculating the q for one fleet component of the total fleet can be achieved simply by partitioning the total F by the ratio of the fleet catch to the total catch, i.e.:

$$F_f = \frac{C_f}{C_T} F_T \tag{35}$$

then:

$$q_f = F_f/E_f \qquad (36)$$

where the subscript f is an index for fleet and T an index for the total fishery. When using only a part of the total catch to tune, the $q_f$ can be calculated for each year and $F_f$ can then be estimated using the geometric mean procedure. The fleet $F_f$ can then be raised to the total $F_T$ by re-arranging the equation above using the catch ratios.

The section above clarifies how the calculations proceed with effort data from one fleet which is only a sub-component of the total catch. Very often this situation is complicated by the fact that effort data exist for several fleets. How can these data be used? In fact it is quite simple. The procedure described for one fleet can be repeated for each fleet for which there are effort data to obtain several estimates of $F_T$. Let us call these estimates $F^f_T$ where the superscript f refers to the estimate from the fth fleet. All we need to do now is combine these estimates into a single input value. Given several estimates of the same quantity might suggest that all we need to do is take a simple mean. If the variance of each estimate of $F_T$, was the same then this would be appropriate. However, some fleets will provide better estimates than others because the data will have different errors. Statistical theory therefore tells us to take a weighted mean where the weight given to each estimate is the inverse of the variance of the estimate. Thus if our combined estimate is $F_T$, then:

$$F_T = \frac{\Sigma W_f F_T^f}{\Sigma W_f} \quad \text{where } W_f = 1/\text{var}(F_T^f) \qquad (37)$$

This outlines the basic calculations in performing Laurec-Shepherd tuning. There are a number of further topics to be dealt with. These include checking that the analysis has not violated the assumptions by examining diagnostics and how to deal with F on the oldest age. These are covered below but in order to consolidate the theory above a simple worked example now follows.

### A simple worked example

The example used for illustration comes from Tables 9 and 14. Catch-at-age data from these tables is reproduced here in Table 15. It is assumed that for the research vessel indices the "effort" is unity for each year.

TABLE 14. Stock numbers and fishing mortality estimates obtained when using the Laurec-Shepherd tuning method on the catch data in Table 9.

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Numbers** | | | | |
| 3 | 1 010 | 1 020 | 2 023 | 2 139 | 1 186 | 1 009 | 1 085 | 1 024 |
| 4 | 775 | 810 | 823 | 1 632 | 1 719 | 955 | 806 | 869 |
| 5 | 556 | 597 | 635 | 645 | 1 259 | 1 331 | 734 | 613 |
| 6 | 322 | 373 | 421 | 448 | 435 | 846 | 865 | 490 |
| 7 | 204 | 192 | 241 | 272 | 268 | 261 | 468 | 496 |
| 8 | 78 | 113 | 117 | 147 | 150 | 149 | 133 | 235 |
| 9 | 91 | 43 | 69 | 71 | 82 | 83 | 75 | 68 |
| | | | | **F** | | | | |
| 3 | .0199 | .0142 | .0148 | .0187 | .0169 | .0244 | .0226 | .0295 |
| 4 | .0601 | .0445 | .0438 | .0591 | .0560 | .0631 | .0738 | .0819 |
| 5 | .1984 | .1487 | .1474 | .1951 | .1972 | .2302 | .2037 | .2959 |
| 6 | .3184 | .2381 | .2373 | .3137 | .3116 | .3931 | .3572 | .3597 |
| 7 | .3904 | .2979 | .2946 | .3948 | .3899 | .4760 | .4878 | .5026 |
| 8 | .3822 | .2919 | .2935 | .3869 | .3875 | .4825 | .4642 | .5743 |
| 9 | .3913 | .2949 | .2941 | .3909 | .3887 | .4787 | .4760 | .5385 |

TABLE 15. Catch-at-age data and research vessel data used for Laurec Shepherd tuning.

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Catch-at-age** | | | | |
| 3 | 18 | 13 | 27 | 36 | 18 | 22 | 22 | 27 |
| 4 | 41 | 32 | 32 | 85 | 85 | 53 | 52 | 62 |
| 5 | 91 | 75 | 79 | 104 | 205 | 249 | 123 | 143 |
| 6 | 80 | 72 | 81 | 110 | 106 | 251 | 237 | 135 |
| 7 | 60 | 45 | 56 | 81 | 79 | 90 | 165 | 179 |
| 8 | 23 | 26 | 27 | 43 | 44 | 52 | 45 | 94 |
| 9 | 27 | 10 | 16 | 21 | 24 | 29 | 26 | 26 |
| | | | | **Research Vessel** | | | | |
| | 2.15 | 2.13 | 3.89 | 3.69 | 2.13 | 2.17 | 2.00 | 1.98 |
| 4 | 4.72 | 4.01 | 4.44 | 8.18 | 7.87 | 3.96 | 5.15 | 4.44 |
| 5 | 4.50 | 4.68 | 4.80 | 5.35 | 10.05 | 9.52 | 4.50 | 4.40 |
| 6 | 3.36 | 3.74 | 3.98 | 4.03 | 4.62 | 9.73 | 6.01 | 4.60 |
| 7 | 2.20 | 1.66 | 2.63 | 2.74 | 2.41 | 2.26 | 3.84 | 4.44 |
| 8 | 0.73 | 1.06 | 1.08 | 1.23 | 1.65 | 1.40 | 1.29 | 2.05 |
| 9 | 0.80 | 0.40 | 0.66 | 0.60 | 0.71 | 0.77 | 0.82 | 0.66 |

First of all we have to start the analysis by setting F on the oldest age. We will fix these as the same values used to generate the data. Using these Fs and the catches for ages 8 and 9 we can calculate the Fs at age 8 (Table 16) using the usual VPA equations.

TABLE 16. Calculation of log catchability for age 8 in 1983.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Fishing Mortalities** | | | | |
| 8 | .397 | .296 | .298 | .395 | .399 | .497 | .495 | |
| 9 | .400 | .300 | .300 | .400 | .400 | .500 | .500 | .600 |
| | | | | **Age 8 Log Catchabilities** | | | | |
| | -4.37 | -4.42 | -4.43 | -4.48 | -4.20 | -4.31 | -4.26 | -4.35 |

Next we partition the F at age 8 into the F for the research vessel fleet. Thus, for example the fleet f ($F^f$) at age 8 in 1976 is given by:

$$\frac{0.73 \times 0.397}{23} = 0.0126 = F^f_{8,78} \qquad (38)$$

To obtain q we divide this by the effort but since it is one for the research vessel it is the same as the fleet F. Thus log catchability in this case is:

$$\log(0.0126) = -4.374 \qquad (39)$$

This calculation can be repeated for each year to obtain the result in Table 16. All we do now is to take an average of the Qs which in this case is -4.35. This mean is the predicted value for 1983. We can calculate the terminal F in 1983 by back transforming Q and scaling up the q using the catch ratio and the effort:

$$F_{8,83} = \exp(-4.35)\ (94/2.05) \times 1 = 0.5897 \qquad (40)$$

This terminal F allows us to run the VPA back to the next age and repeat the calculation for that input F. Doing this for all ages leads to the result in Table 17. Finally the whole procedure gives a complete table of F and stock number at age (Table 18).

TABLE 17. Calculation of terminal Fs using Laurec-Shepherd tuning.

| | Log catchability estimates | | | | | | | | q = | C(total)E | Raised |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | $\overline{Q}$ | exp(Q) | C(fleet) | F(1983) |
| 3 | -6.03 | -6.05 | -6.14 | -6.25 | -6.21 | -6.02 | -6.18 | -6.13 | .0022 | 13.60 | .0298 |
| 4 | -4.96 | -5.18 | -5.08 | -5.16 | -5.25 | -5.35 | -4.91 | -5.13 | .0059 | 13.96 | .0827 |
| 5 | -4.62 | -4.67 | -4.70 | -4.58 | -4.63 | -4.72 | -4.89 | -4.69 | .0092 | 32.50 | .2993 |
| 6 | -4.31 | -4.38 | -4.44 | -4.45 | -4.27 | -4.17 | -4.69 | -4.39 | .0124 | 29.35 | .3646 |
| 7 | -4.24 | -4.50 | -4.27 | -4.30 | -4.41 | -4.39 | -4.46 | -4.37 | .0127 | 40.32 | .5121 |
| 8 | -4.37 | -4.42 | -4.43 | -4.48 | -4.20 | -4.31 | -4.26 | -4.35 | .0129 | 45.85 | .5897 |

TABLE 18. Estimated fishing mortality rate and stock in numbers from Laurec-Shepherd tuning.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **F at Age** | | | | |
| 3 | .0201 | .0144 | .0149 | .0189 | .0170 | .0246 | .0228 | .0298 |
| 4 | .0607 | .0450 | .0446 | .0595 | .0565 | .0637 | .0744 | .0827 |
| 5 | .2001 | .1504 | .1490 | .1992 | .1987 | .2323 | .2058 | .2993 |
| 6 | .3212 | .2407 | .2405 | .3181 | .3200 | .3970 | .3615 | .3646 |
| 7 | .3945 | .3016 | .2987 | .4024 | .3976 | .4943 | .4955 | .5121 |
| 8 | .3970 | .2963 | .2983 | .3945 | .3985 | .4973 | .4950 | .5897 |
| 9 | .4000 | .3000 | .3000 | .4000 | .4000 | .5000 | .5000 | .6000 |
| | | | | **Number at Age (Start of Year)** | | | | |
| 3 | 1 000 | 1 002 | 2 010 | 2 124 | 1 176 | 1 000 | 1 075 | 1 014 |
| 4 | 767 | 803 | 809 | 1 622 | 1 706 | 946 | 799 | 860 |
| 5 | 552 | 591 | 628 | 633 | 1 251 | 1 320 | 727 | 607 |
| 6 | 320 | 370 | 416 | 443 | 425 | 840 | 857 | 485 |
| 7 | 202 | 190 | 238 | 268 | 264 | 253 | 462 | 489 |
| 8 | 77 | 111 | 115 | 145 | 147 | 145 | 126 | 231 |
| 9 | 90 | 42 | 68 | 70 | 80 | 81 | 72 | 63 |

## Advanced Topics

The above section concentrated on the basic ideas behind tuning using catch and effort data as used by ICES. This section deals with some unfinished business and fills in some of the details of the tuning procedure as well as dealing with the interpretation of the results of the analysis.

## Fishing mortality on the oldest age

So far with tuning, only F in the terminal year has been dealt with. However, it is necessary also to try to get the best estimates of F on the oldest age group. This is a very difficult problem because catch-at-age data contain very little information on F at the highest age. Most methods have to make certain assumptions about the shape of the selectivity pattern or how the exploitation pattern changes with age. The nature of the gear selectivity characteristics of trawls and similar towed gears is such that the conventional assumption is that selectivity rises with age to a plateau, i.e. the exploitation pattern is "flat topped". However, there are many reasons why this may not be so. For example, older fish may occur in a different location from younger ones and if the fishery concentrates on the younger fish (because they are more abundant), the selectivity can be dome shaped. Some thought therefore has to be given to the assumption made.

In the ICES tuning package the assumption made is that F on the oldest age in a particular year, $F_{a,y}$, is a fixed multiple of the mean F over a range of younger ages in the same year:

$$F_{a,y} = s \sum_{k=i}^{j} F_{k,y/j-i+1} \qquad (41)$$

where i and j are the indices for the age range over which the mean is calculated and s is a scaling value. If s = 1 then the exploitation pattern will tend to be flat topped. For s<1 the exploitation pattern will be domed.

In the description of the Laurec-Shepherd method above, the solution was unique for any fixed set of Fs on the oldest age. Now if these Fs are revised using the above formula, a new F-at-age matrix can be generated. This means the tuning procedure has to be iterated with F on the oldest age revised at each cycle until the estimates converge. It is important to appreciate that convergence is not guaranteed and this procedure may not work if the Fs are very low. In general, however, convergence is achieved after a few iterations.

## Diagnostics

Whatever the approach used to analyse catch-at-age and effort data certain assumptions are either explicitly made or are implicit in the method. Wherever possible attempts should be made to verify that the assumptions made are not violated. If they are, then the results of the analysis may be unreliable or simply wrong. Unfortunately it is often very difficult to prove that assumptions have been contravened. At best all that can be done is to show that nothing in the data can be detected which breaks the assumptions.

Perhaps the best way to understand the use of diagnostics is to use an example. Once again we will use the test data given in Table 15. That example uses only one tuning fleet. To make it a little more illustrative a second tuning fleet is introduced here with the data in Table 19. A full Laurec-Shepherd tuning has been done on these data using the method described above to estimate F on the oldest age. In fact F at age 9 has be set to the mean of ages 7 and 8 in each year. The results of the tuning are shown on Tables 20 and 21.

TABLE 19. Second research vessel survey indices used in Laurec-Shepherd tuning.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| 3 | .022 | .040 | .140 | .162 | .107 | .159 | .143 | .159 |
| 4 | .045 | .088 | .127 | .328 | .410 | .223 | .388 | .373 |
| 5 | .404 | .095 | .140 | .210 | .510 | .584 | .298 | .356 |
| 6 | .036 | .071 | .112 | .167 | .211 | .607 | .442 | .350 |
| 7 | .025 | .032 | .092 | .101 | .116 | .120 | .280 | .378 |
| 8 | .009 | .026 | .039 | .034 | .077 | .067 | .101 | .186 |
| 9 | .003 | .014 | .024 | .022 | .044 | .032 | .079 | .044 |

In Table 20 the residuals from the fitted (mean) log catchabilities are shown. Our assumption was that there was no trend in catchability. For the fleet RVS1 there is no obvious trend with time but for RVS2 all the negative residuals are in the early years. This implies there is an increasing trend in q and immediately gives cause for concern about the reliability of the results. Patterns in residuals often indicate systematic deviations from the model assumptions and if such patterns occur they should be investigated further to check that the results are not seriously affected.

TABLE 20. Residuals of log catchabilities (Q) when using Laurec Shepherd tuning with two fleets.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| **Fleet :RVS1** | | | | | | | | |
| 3 | .11 | .08 | .00 | -.11 | -.09 | .10 | -.08 | -.01 |
| 4 | .18 | -.04 | .05 | -.02 | -.12 | -.23 | .21 | -.03 |
| 5 | .08 | .03 | -.01 | .10 | .07 | -.03 | -.23 | -.02 |
| 6 | .10 | .02 | -.04 | -.06 | .11 | .22 | -.31 | -.04 |
| 7 | .14 | -.12 | .11 | .07 | -.04 | -.05 | -.10 | -.02 |
| 8 | .00 | -.05 | -.06 | -.12 | .15 | .04 | .05 | -.01 |
| **Fleet :RVS2** | | | | | | | | |
| 3 | -1.21 | -.63 | -.37 | .02 | .17 | .74 | .54 | .72 |
| 4 | -1.20 | -.59 | -.24 | .03 | .19 | .16 | .89 | .76 |
| 5 | -1.33 | -.57 | -.24 | .16 | .38 | .47 | .36 | .77 |
| 6 | -1.15 | -.66 | -.33 | .05 | .31 | .73 | .37 | .68 |
| 7 | -1.06 | -.81 | .03 | .03 | .19 | .28 | .55 | .78 |
| 8 | -1.19 | -.49 | -.12 | -.43 | .35 | .25 | .77 | .85 |

Table 21 gives more detailed statistics about the results. The predicted log catchability and its standard errors are given for each age group. A quick scan over the table shows that the standard error for fleet 2 (RVS2) is much higher than RVS1. This means the estimate of $F_T$ from this fleet will be less reliable. Also shown in this table is the slope of the Qs with time. For RVS1 the slope is close to and not significantly different from zero as we have assumed in the model. For RVS2, however, the slope is positive and

TABLE 21. Summary statistics after Laurec-Shepherd tuning with two fleets.

| Fleet | Predicted Q | Standard error Q | Partial F | Raised F | Standard Slope | Error | Intercept | Standard Error |
|---|---|---|---|---|---|---|---|---|
| | | | | **Age 3** | | | | |
| RVS 1 | -6.15 | .095 | .0021 | .0289 | -.162E-01 | .134E-01 | -6.155 | .032 |
| RVS 2 | -9.41 | .736 | .0001 | .0139 | .271E+00 | .334E-01 | -9.412 | .245 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .029 | .944E-01 | | .932E-01 | | .944E-01 | | .973 | |
| | | | | **Age 4** | | | | |
| 1 | -5.16 | .155 | .0058 | .0806 | -.144E-01 | .237E-01 | -5.155 | .052 |
| 2 | -8.42 | .727 | .0002 | .0366 | .268E+00 | .332E-01 | -8.422 | .242 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .078 | .152 | | .162 | | .162 | | 1.130 | |
| | | | | **Age 5** | | | | |
| 1 | -4.71 | .110 | .0090 | .2924 | -.251E-01 | .140E-01 | -4.711 | .037 |
| 2 | -8.01 | .724 | .0003 | .1336 | .258E+00 | .430E-01 | -8.007 | .241 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .287 | .109 | | .117 | | .117 | | 1.145 | |
| | | | | **Age 6** | | | | |
| 1 | -4.41 | .166 | .0121 | .3558 | -.193E-01 | .249E-01 | -4.413 | .055 |
| 2 | -7.70 | .705 | .0005 | .1745 | .254E+00 | .386E-01 | -7.700 | .235 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .343 | .162 | | .159 | | .162 | | .968 | |
| | | | | **Age 7** | | | | |
| 1 | -4.39 | .103 | .0124 | .4989 | -.191E-01 | .142E-01 | -4.392 | .034 |
| 2 | -7.66 | .672 | .0005 | .2235 | .245E+00 | .332E-01 | -7.657 | .224 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .490 | .102 | | .121 | | .121 | | 1.396 | |
| | | | | **Age 8** | | | | |
| 1 | -4.39 | .087 | .0124 | .5704 | .117E-01 | .128E-01 | -4.387 | .029 |
| 2 | -7.65 | .734 | .0005 | .2410 | .267E+00 | .373E-01 | -7.650 | .245 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .564 | .864E-01 | | .101 | | .101 | | 1.359 | |

significantly different from zero. This means there is probably a trend in the catchability of this fleet and indicates there is a problem with the analysis since our assumption about constant catchability is wrong for fleet 2. It can be seen from the table that the estimate of $F_T$ (the raised F column) from this fleet is consistently below that for the other fleet and may be causing bias. We could repeat the analysis and try to fit a trend to one of the fleets. This approach is often referred to as the hybrid method but it should only be tried with considerable care since extrapolating a log linear trend in Q can be very dangerous. In fact in this example fleet 2 has very little influence on the final result because it has high variance and therefore received low weight in calculating the tuned F. In these circumstances it is probably best to leave fleet 2 out of the final analysis since it is contributing very little useful information.

The diagnostics described so far will be familiar to most people. We now come onto something a little harder. The last line in each "summary statistics" section gives "SIGMA(int)" and "SIGMA(ext)". These are two estimates of the standard error of the final estimate of terminal F after combining the individual estimates from each fleet. The "internal" Standard error is that obtained from the weighted sum of the variances of each individual $F^f_T$. The "external" Standard error is obtained from the variance of the predicted $F^f_T$ around the mean. These two standard error estimates (SIGMA(int)) + sigma (ext)) should be the same so that the variance ratio ext/int should be unity. If the ratio is very large (>3), this indicates the individual fleet estimates are inconsistent, i.e. the error bars for each individual estimate of $F_T$ do not overlap. In other words they are predicting different things. If the variance ratio is very low (<0.3), the estimates agree more closely than their precision merits and also this suggests something suspicious in the data.

These diagnostics can help identify problems. Unfortunately there is often very little that can be done in practice to put things right, though a few suggestions are given below. Sometimes troublesome data sets can be left out but this can't be done if they are the only data available. However, it is important to know the shortcomings of the analysis so that the estimated values from the analysis can be interpretted correctly.

## Weighting the observations

As has been mentioned before, catchability, especially for commercial fleets is likely to change with time. This means that any method which assumes constant catchability may run into problems. If the change in q with time is slow and gradual then one way of avoiding difficulties is to limit any analysis to a period of recent years. This is effectively giving older data zero weight. An alternative is to give older observations lower but non-zero weight. A common practice in ICES is to use a weighting function which gives historical observations progressively lower weight. This function has the form:

$$\left[1-\left(\frac{D}{D_{max}}\right)^n\right]^n \qquad (42)$$

where D is the distance of the point to be weighted from the most recent year, $D_{max}$ is the maximum distance in the time series and n is a number to be specified which determines the rate at which the weight decreases backward in time. For n = 1 the weights decline linearly. Typically n is set at 3 in ICES assessments. This value gives similar weight to observations in recent years but rapidly downweights older data.

It is important to understand that this weighting procedure is a purely *ad hoc* practical device which does not have any formal statistical justification and many experts disapprove of its use. It remains in use for many assessments simply because it appears to work. To some degree it will ameliorate problems with trends in q because the mean will be heavily weighted towards those observations at the end of the time trend. It is probably better to use weighting of this type to overcome trend problems than to fit trends to q.

### Shrinkage

Catchability tuning has two main inherent problems. One of these, the problem of trends in q has been referred to frequently. The other is that the estimate of terminal F is subject to large errors. This is because raw catch and effort data are used to derive the terminal value and they will usually be subject to error. Where several fleets are used in tuning, the problem will be diminished because the result is a weighted mean. When only one or two fleets are used, however, the problem may be severe. This problem and that of unwanted trends in q can be reduced by so called "shrinkage".

Shrinkage is a means whereby the final estimate of $F_T$ is 'shrunk' towards the overall mean F at that age. Let us suppose that we have tuned a VPA in the usual way and that the estimated terminal F is $F_T$ . For any age there are also historical Fs for each year in the F at age table. These values will be 'converged values' and we can take a mean of these, $\bar{F}$. This mean could also be regarded as an estimator of $F_T$ and it is likely to be a good estimator if the exploitation of the fishery is similar from year to year. Thus we might consider taking a weighted mean of $F_T$ and $\bar{F}$. That is:

$$\frac{1}{(1+w)}(F_T + w\bar{F}) \qquad (43)$$

where w is an appropriately chosen weight. The choice of weight will depend on what degree of shrinkage is desired. The use of inverse variance weighting is likely to be suitable in many circumstances.

When there are trends in q resulting in a bias in the estimate of terminal F, shrinkage may reduce the bias if there is no trend in F. If, however, the tuned terminal F is unbiased shrinkage may introduce bias if there is a trend in F. But because $\bar{F}$ is likely to be of higher precision it can improve the overall precision of the result. Where the tuned value is very imprecise, the improvement in precision achieved through shrinkage may outweigh the introduction of bias.

## North Sea Cod Example

### Introduction

So far all the examples used to demonstrate tuning have been from simulated data. Generally real data are a lot 'nastier' than most artificial data sets, so it is worthwhile looking at a real data set to see how the analysis might work in practice. The example used here is the North Sea cod. A great deal of both commercial catch and effort data and research vessel data are available for this stock. In order to make things a little more simple in this example only four fleets have been chosen; two commercial vessel series (Scottish trawlers – SCOLTR and English trawlers – ENGTRL) and two research vessel survey series (English Groundfish survey – ENGGFS and International Young Fish Survey – INTGFS). The data are for the years 1978–87 and are shown in Table 22. In fact the most recent assessment for this stock goes up to 1990 so we can compare our results in this example with the converged VPA values using all the available data done by the Roundfish Working Group (Anon. 1991b).

TABLE 22. Total catch-at-age data and fleet catch and effort data for North Sea cod used for Laurec-Shepherd tuning, 1978–87.

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Age | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 |
| | | | | | **Total catch-at-age** | | | | | |
| 1 | 24 933 | 34 116 | 60 874 | 19 835 | 64 839 | 23 838 | 63 860 | 7 894 | 82 594 | 21 635 |
| 2 | 158 837 | 85 845 | 96 115 | 175 922 | 59 947 | 121 828 | 57 774 | 111 120 | 20 828 | 105 618 |
| 3 | 13 094 | 40 459 | 29 562 | 27 563 | 53 239 | 17 518 | 27 765 | 15 712 | 28 919 | 6 962 |
| 4 | 8 417 | 3 332 | 10 272 | 7 649 | 7 287 | 10 104 | 3 461 | 6 875 | 3 954 | 7 625 |
| 5 | 2 809 | 3 130 | 1 590 | 3 802 | 3 193 | 2 501 | 3 119 | 1 150 | 2 584 | 1 348 |
| 6 | 941 | 675 | 1 172 | 740 | 1 883 | 1 167 | 939 | 1 116 | 521 | 955 |
| 7 | 366 | 365 | 412 | 555 | 355 | 562 | 415 | 328 | 498 | 209 |
| 8 | 372 | 129 | 191 | 131 | 218 | 142 | 233 | 162 | 148 | 188 |
| 9 | 140 | 145 | 71 | 63 | 72 | 70 | 57 | 73 | 60 | 46 |
| 10 | 73 | 54 | 78 | 56 | 40 | 40 | 61 | 36 | 58 | 42 |
| | | | | | **Catch and effort for Scottish Trawlers (SCOLTR)** | | | | | |
| 1 | 2 256 | 1 973 | 1 849 | 691 | 4 704 | 1 321 | 2 724 | 431 | 4 140 | 2 045 |
| 2 | 5 379 | 5 845 | 5 356 | 5 237 | 2 940 | 6 293 | 3 023 | 5 959 | 1 167 | 5 663 |
| 3 | 671 | 1 808 | 2 101 | 1 475 | 2 302 | 1 020 | 1 544 | 865 | 1 848 | 530 |
| 4 | 270 | 178 | 549 | 294 | 377 | 460 | 180 | 294 | 251 | 468 |
| 5 | 51 | 61 | 71 | 82 | 110 | 111 | 86 | 39 | 96 | 45 |
| 6 | 28 | 15 | 16 | 11 | 39 | 31 | 36 | 21 | 12 | 31 |
| 7 | 7 | 3 | 4 | 6 | 8 | 14 | 10 | 4 | 9 | 10 |
| Eff | 236 929 | 207 494 | 333 197 | 251 504 | 250 870 | 244 349 | 240 725 | 268 136 | 279 767 | 351 131 |
| | | | | | **Catch and effort for English Trawlers (ENGTRL)** | | | | | |
| 1 | 2 029 | 1 329 | 1 881 | 615 | 4 074 | 711 | 3 469 | 675 | 9 097 | 447 |
| 2 | 10 576 | 7 698 | 3 786 | 12 703 | 3 063 | 14 220 | 3 459 | 8 212 | 2 107 | 10 435 |
| 3 | 1 093 | 3 341 | 2 106 | 1 886 | 3 802 | 1 185 | 2 656 | 1 047 | 2 388 | 682 |
| 4 | 987 | 393 | 865 | 535 | 587 | 907 | 267 | 533 | 209 | 596 |
| 5 | 338 | 403 | 122 | 250 | 298 | 127 | 217 | 72 | 161 | 36 |
| 6 | 117 | 99 | 114 | 38 | 179 | 87 | 42 | 54 | 15 | 26 |
| 7 | 57 | 54 | 38 | 48 | 35 | 49 | 32 | 16 | 12 | 3 |
| 8 | 60 | 15 | 16 | 8 | 24 | 16 | 16 | 10 | 4 | 4 |
| 9 | 22 | 30 | 6 | 6 | 11 | 4 | 3 | 4 | 2 | 2 |
| Eff | 559 930 | 553 020 | 442 036 | 423 658 | 424 272 | 392 364 | 358 387 | 342 844 | 288 867 | 275 899 |
| 2 | 1.41 | .679 | .77 | 1.582 | .209 | .81 | .388 | .868 | .094 | .82 |
| 3 | .111 | .234 | .176 | .145 | .237 | .089 | .146 | .078 | .166 | .021 |
| 4 | .112 | .032 | .084 | .044 | .038 | .082 | .033 | .041 | .024 | .047 |
| | | | | | **Catch and effort for English Groundfish Survey (ENGGFS)** | | | | | |
| 1 | 2.577 | 2.835 | 5.839 | 1.296 | 2.329 | 1.138 | 5.014 | .314 | 2.817 | 1.095 |
| 5 | .015 | .042 | .013 | .046 | .027 | .021 | .017 | .015 | .009 | .011 |
| Eff | 113 | 117 | 115 | 114 | 72 | 74 | 82 | 73 | 82 | 77 |
| | | | | | **Catch and effort data for International Young Fish Survey (INTGFS)** | | | | | |
| 1 | .013 | .01 | .017 | .003 | .009 | .004 | .015 | .001 | .017 | .009 |
| 2 | .029 | .009 | .015 | .026 | .007 | .017 | .008 | .018 | .004 | .029 |
| Eff 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |

## Tuning analysis

Using the data in Table 22 a preliminary Laurec-Shepherd tuning run has been performed using the basic methodology with no fancy weighting or shrinkage. Our first task is to examine the residuals from the fitted log catchabilities. These are plotted for the four fleets in Fig. 1. With the exception of INTGFS, all the fleets show some indication of an increase in catchability. The tendency for neutral residuals at the end of the time series is an inevitable consequence of using mean Q to tune F. There is good reason to suppose, therefore, that the results may be affected by trends.

The summary statistics from the tuning are shown in Table 23. For each age the predicted terminal F is given by fleet. It is noticeable that the predicted values vary a

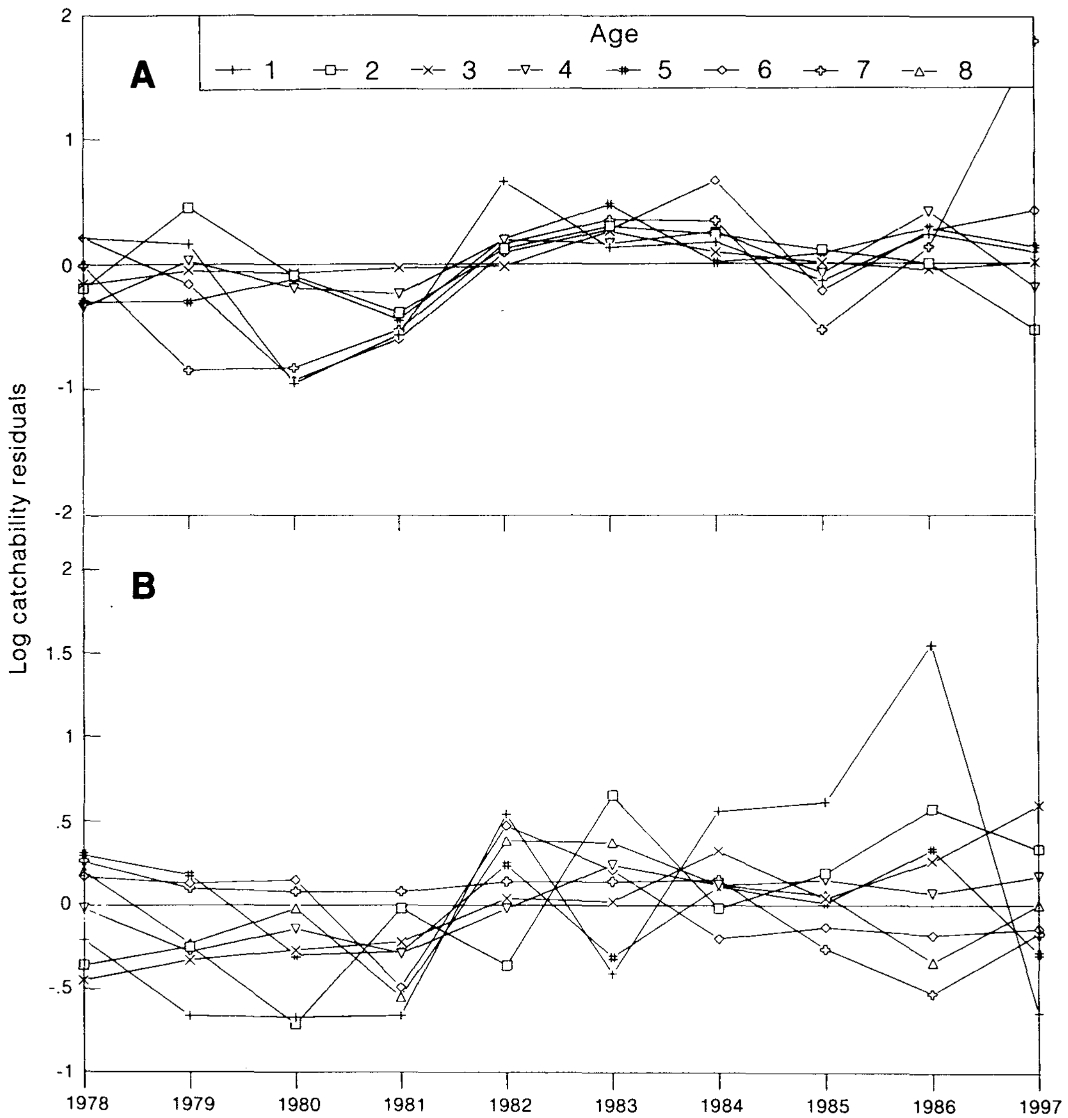


Fig. 1. Plots of log catchability residuals against time for four fleets; (**A**) Scottish trawlers (SCOLTR), (**B**) English trawlers (ENGTRL), (**C**) English Groundfish Survey (ENGGFF), and (**D**) International Young Fish Survey (INTGFS), used in tuning North Sea cod.

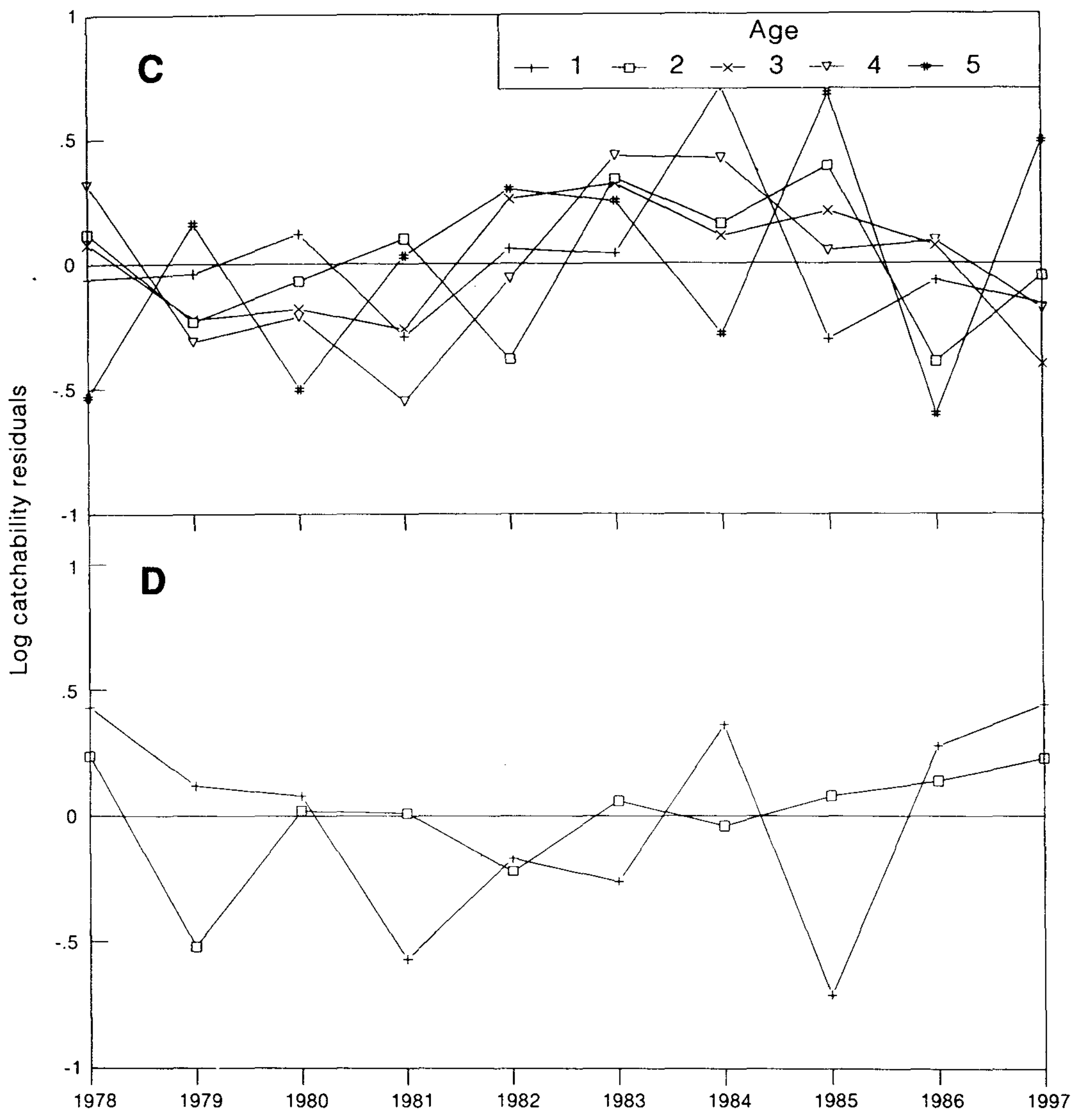


Fig. 1. (Continued) Plots of log catchability redisuals against time for four fleets; (**A**) Scottish trawlers (SCOLTR), (**B**) English trawlers (ENGTRL), (**C**) English Groundfish Survey (ENGGFF), and (**D**) International Young Fish Survey (INTGFS), used in tuning North Sea cod.

lot between fleets and that the predicted terminal F by each fleet has a large standard error. Nevertheless because four fleets are available the standard errors for the combined terminal F (SIGMA (overall)) is considerably lower. In general the variance ratio is acceptable although for age 7 there is a problem. This combined with the fact that the standard errors for the predicted terminal F on the oldest ages suggests these values are poorly estimated. In fact the absolute values of F at about age 2 appears to be very large.

Although the slopes of the catchability trends are generally positive, they are not significant, thus the results are probably not severely affected by such trends.

What then do the diagnostics tell us? Firstly there is possibly a small problem of trends and secondly the estimates on the older ages are subject to a large error. The first problem is probably best dealt with by giving the older data lower weight. The large error problem is likely to be hepled by shrinkage since the mean F at any age will tend to be better estimated than the tuned value. In view of this the analysis has been re-run with a weighting function with n = 3 and shrinkage. The best way to judge the improvement in the result is to compare the predicted Fs for 1987 against the converged values from the full VPA. These are shown in Fig. 2. The revised tuning gives a substantially closer estimate. of the converged values than the preliminary run for the older ages. Nearly all the improvement is due to the use of shrinkage and this illustrates what a useful tool it can be in the right circumstances.

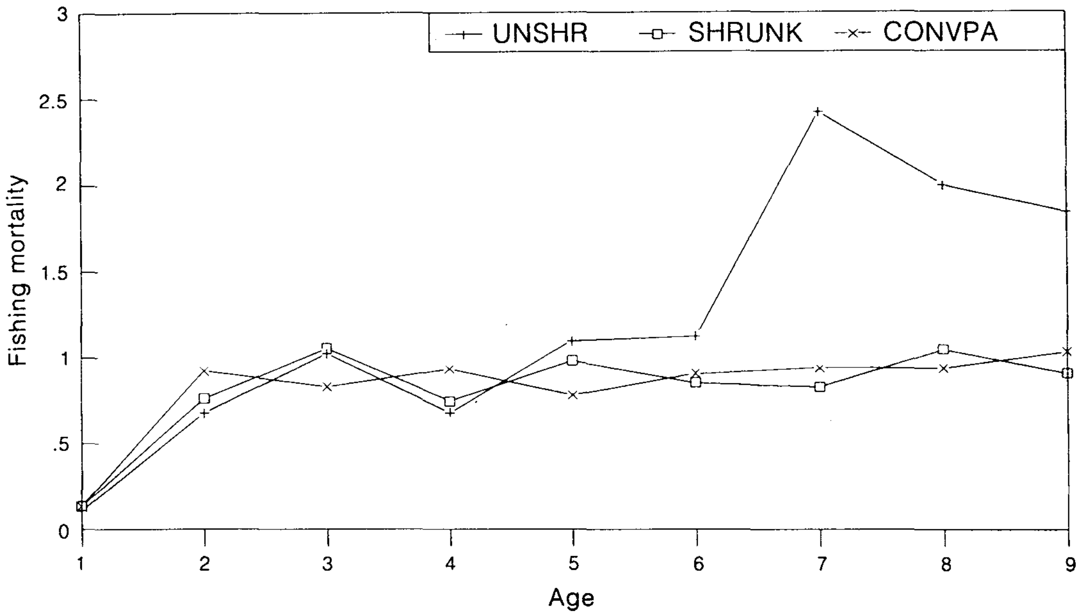


Fig. 2. Estimated terminal fishing mortalities for North Sea cod in 1987. UNSHR is tuning using the four fleets without weighting or shrinkage. SHRUNK is the same tuning but including tri-cubic weighting and shrinkage of the final estimate of F towards the mean. CONVPA is the converged exploitation pattern from a VPA with 1990 as the terminal year.

TABLE 23. Summary statistics for Laurec-Shepherd tuning for North Sea cod (ages 1–8).

| Fleet | Predicted Q | Standard Error Q | Partial F | Raised F | Slope | Standard Error | Intercept | Standard Error |
|---|---|---|---|---|---|---|---|---|
| | | | | **Age 1** | | | | |
| SCOLTR | -17.41 | .477 | .0096 | .1019 | 313E-01 | .520E-01 | -17.411 | .144 |
| ENGTRL | -17.96 | .803 | .0044 | .2117 | 125E+00 | .777E-01 | -17.960 | .242 |
| ENGGFS | -16.27 | .301 | .0000 | .1310 | -.925E-03 | .335E-01 | -16.267 | .091 |
| INTGFS | -17.32 | .432 | .0000 | .0723 | -.307E-03 | .481E-01 | -17.320 | .130 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .112 | .212 | | .171 | | .212 | | .656 | |
| | | | | **Age 2** | | | | |
| SCOLTR | -15.55 | .322 | .0618 | 1.1534 | -.194E-01 | .352E-01 | -15.552 | .097 |
| ENGTRL | -15.56 | .458 | .0482 | .4882 | .106E+00 | .347E-01 | -15.560 | .138 |
| ENGGFS | -16.45 | .287 | .0000 | .7088 | .334E-02 | .319E-01 | -16.454 | .087 |
| INTGFS | -15.73 | .236 | .0000 | .5362 | .300E-01 | .240E-01 | -15.731 | .071 |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .676 | .150 | | .178 | | .178 | | 1.415 | |
| | | | | **Age 3** | | | | |
| SCOLTR | -15.34 | .118 | .0767 | 1.0069 | .157E-01 | .119E-01 | -15.337 | .035 |
| ENGTRL | -15.42 | .340 | .0554 | .5659 | .101E+00 | .132E-01 | -15.420 | .103 |
| ENGGFS | -16.64 | .257 | .0000 | 1.5158 | .488E-02 | .286E-01 | -16.639 | .078 |
| INTGFS | | | No data for this fleet at this age | | | | | |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| 1.020 | .102 | | .167 | | .167 | | 2.691 | |
| | | | | **Age 4** | | | | |
| SCOLTR | -15.76 | .258 | .0505 | .8219 | .361E-01 | .257E-01 | -15.755 | .078 |
| ENGTRL | -15.63 | .194 | .0449 | .5740 | .431E-01 | .154E-01 | -15.632 | .059 |
| ENGGFS | -16.55 | .341 | .0000 | .8092 | .185E-01 | .374E-01 | -16.552 | .103 |
| INTGFS | | | No data for this fleet at this age | | | | | |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| .678 | .141 | | .125 | | .141 | | .781 | |
| | | | | **Age 5** | | | | |
| SCOLTR | -16.20 | .302 | .0323 | .9586 | .642E-01 | .249E-01 | -16.203 | .091 |
| ENGTRL | -15.77 | .280 | .0390 | 1.4597 | -.122E-01 | .309E-01 | -15.772 | .084 |
| ENGGFS | -16.46 | .475 | .0000 | .6699 | .533E-01 | .494E-01 | -16.460 | .143 |
| INTGFS | | | No data for this fleet at this age | | | | | |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| 1.096 | .189 | | .203 | | .203 | | 1.158 | |
| | | | | **Age 6** | | | | |
| SCOLTR | -16.49 | .509 | .0243 | .7360 | .753E-01 | .500E-01 | -16.488 | .153 |
| ENGTRL | -15.88 | .290 | .0350 | 1.2868 | -.348E-01 | .298E-01 | -15.879 | .087 |
| ENGGFS | | | No data for this fleet at this age | | | | | |
| INTGFS | | | No data for this fleet at this age | | | | | |
| Fbar | SIGMA(int.) | | SIGMA(ext.) | | SIGMA(overall) | | Variance ratio | |
| 1.123 | .252 | | .240 | | .252 | | .910 | |

TABLE 23. Continued.

| Fleet | Predicted Q | Standard Error Q | Partial F | Raised F | Slope | Standard Error | Intercept | Standard Error |
|---|---|---|---|---|---|---|---|---|
| | | | | **Age 7** | | | | |
| SCOLTR | -16.67 | .810 | .0201 | .4125 | .165E+00 | .690E-01 | -16.675 | .244 |
| ENGTRL | -15.71 | .254 | .0414 | 2.8796 | -.594E-01 | .190E-01 | -15.712 | .077 |
| ENGGFS | | | No data for this fleet at this age | | | | | |
| INTGFS | | | No data for this fleet at this age | | | | | |

| Fbar | SIGMA(int.) | SIGMA(ext.) | SIGMA(overall) | Variance |
|---|---|---|---|---|
| 2.419 | .243 | .555 | .555 | 5.234 |

| Fleet | Predicted Q | Standard Error Q | Partial F | Raised F | Slope | Standard Error | Intercept | Standard Error |
|---|---|---|---|---|---|---|---|---|
| | | | | **Age 8** | | | | |
| SCOLTR | | | No data for this fleet at this age | | | | | |
| ENGTRL | -15.69 | .316 | .0424 | 1.9937 | -.115E-02 | .352E-01 | -15.689 | .095 |
| ENGGFS | | | No data for this fleet at this age | | | | | |
| INTGFS | | | No data for this fleet at this age | | | | | |

| Fbar | SIGMA(int.) | SIGMA(ext.) | SIGMA(overall) | Variance ratio |
|---|---|---|---|---|
| 1.994 | .316 | 0.000 | .316 | 0.000 |

# IV. ADAPT

## Introduction

ADAPT is an amalgamation of traditional SPA data and equations with a mathematical procedure to estimate the model parameters. It is extremely versatile and can 'adapt' to any model formulation. The most commonly used models are age disaggregated using only a few tuning indices, typically 3 or less. The model has two types of parameters: Fs for some ages in the terminal year and qs to relate cohort numbers to the survey, the same scaling coefficients as were used in the Laurec-Sheppherd method.

## Model

In our example the F parameters are for ages 4 to 7 and will be directly estimated by the non-linear least squares (NLLS) algorithm in ADAPT. The Fs for ages 3, 8 and 9 are then derived by assuming a partial recruitment pattern. The ratio of the Fs for ages 4–7 are compared to the average partial recruitment for those ages and applied to the remaining ages to infer F. The q parameters are also for ages 4–7 and they link, the Ns derived from the catch and Fs using cohort equations, to the survey values for those ages (Table 24). Although we have survey data for ages 3–9 in this example only 4 ages are chosen. This may be done when the reliability of the survey for the oldest and youngest animals is questioned. The process is shown schematically in Figure 3.

TABLE 24. Research vessel catch-at-age data used for calibration in sample ADAPT and Laurec-Shepherd tuning.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| 3 | 21.5 | 21.3 | 38.9 | 36.9 | 21.3 | 21.7 | 20.0 | 19.8 |
| 4 | 47.2 | 40.1 | 44.4 | 81.8 | 78.7 | 39.6 | 51.5 | 44.4 |
| 5 | 45.0 | 46.8 | 48.0 | 53.5 | 100.5 | 95.2 | 45.0 | 44.0 |
| 6 | 33.6 | 37.4 | 39.8 | 40.3 | 46.2 | 97.3 | 60.1 | 46.0 |
| 7 | 22.0 | 16.6 | 26.3 | 27.4 | 24.1 | 22.6 | 38.4 | 44.4 |
| 8 | 7.3 | 10.6 | 10.8 | 12.3 | 16.5 | 14.0 | 12.9 | 20.5 |
| 9 | 8.0 | 4.0 | 6.6 | 6.0 | 7.1 | 7.7 | 8.2 | 6.6 |

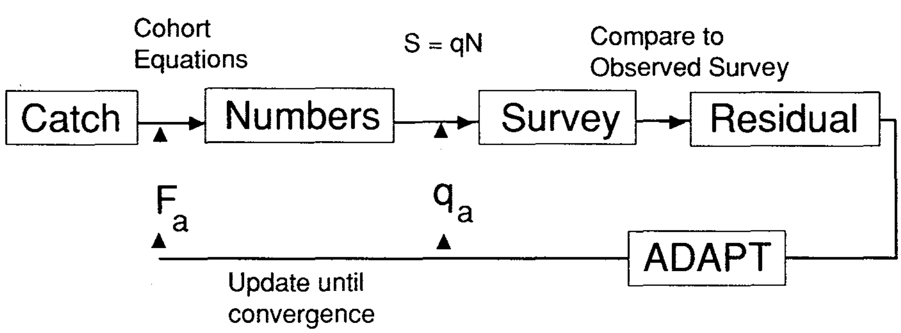


Fig. 3. Schematic representation of ADAPT parameter estimation.

Our example has 8 parameters which are fitted to 32 (8 years times 4 ages) observations from the survey data. As above the natural mortality is 0.2 and the correct partial recruitment is used. The fitting procedure in ADAPT, known as the Marquardt algorithm, requires initial guesses for the parameters. There are many algorithms which could do the non-linear estimation and the Marquardt may not be the best. Research is continuing on alternate methods for the NLLS. Initial guesses are required for the Fs on the oldest age. The F parameters as well as the Fs on the oldest age were initialized at 0.4, and the q parameters at 0.1. Table 25 shows a few of the iterations of ADAPT, and iteration #0 uses initial values. The NLLS algorithm changes the parameters to minimize the residual sum of squares. The difference between the predicted survey values ($S_{Pred}$) and the observed values ($S_{Obs}$) is generally known as a residual (Resid.).

$$Resid_{a,y} = (\ln 1 + S_{Obs_{a,y}}) - (\ln 1 + S_{Pred_{a,y}}) \quad (44)$$

In the version of ADAPT used in this example the logarithm of 1 plus the survey value is used to define the residual. This is done because of the assumption that the errors in the survey are lognormal, a common assumption. If all the residuals are squared and then summed the result is known as the residual sum of squares, RSS. Iteration #0 in Table 25 shows that with the initial parameter estimates, the RSS is 4.8. The residual table is shown beneath the initial parameter values. The residuals for the first age estimated, age 4, tend to be large and negative. Thus the predictions are too small and the parameters will be adjusted to correct this.

The iteration #1, has an RSS of 1.8. The F parameters of ages 4 and 5 have been reduced by the algorithm from the initial guesses of 0.4, while the Fs for ages 6 and 7 have gone up to 0.487 and 0.590, respectively The large negative residuals on age 4 have been significantly reduced except for the 1983 value.

Iteration #2 shows a slight improvement with an RSS of 1.4. After 13 iterations the procedure stops and the residuals for the iteration #13 and parameter values are shown. The RSS is now 0.3. In practice the details of the iterations are not scrutinized and are included here only as illustrations of the internal working of ADAPT.

ADAPT provides summary statistics which provide insights as to how well the model fits the data. Table 26 show the diagnostics for two of our earlier runs. The Mean Square Residual is an indication of how well the average data point is fitted. Table 26 also contains the final parameter values under the column PAR. EST and the standard errors under the column STD.ERR. The ratio of the standard error and the parameter estimate is the coefficient of variation CV% and is expressed here as a percent. The CVs for the Fs range from 10 to 14% , while those for the qs are around 4-5%, which indicates that the qs are much better estimated. The inverse of the CVs is the Students t value, and are shown in the column labeled T. The final column, BIAS %, is the estimate of the bias of each parameter expressed as a percent. These values are used to estimate the bias introduced by the NLLS fit and the model. In our example the biases range from –7 to –19%. The fact that they are negative indicate that the true parameter values should be increased accordingly.

TABLE 25. Sample output of ADAPT run with data from Tables 9 and 14.

*Iteration #0,*
Residual sum of squares = 4.8
Parameter values = .400 .400 .400 .400 .1000 .1000 .1000 .1000

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Residuals** | | | | |
| 4 | –.553 | –.742 | –.582 | –.659 | –.877 | –.801 | –.213 | .736 |
| 5 | –.199 | –.309 | –.326 | –.157 | –.197 | –.439 | –.413 | –.077 |
| 6 | .048 | .011 | –.134 | –.161 | .094 | .172 | –.491 | .022 |
| 7 | .215 | –.130 | .097 | –.089 | –.179 | –.087 | –.140 | –.287 |

*Iteration #1,*
Residual sum of squares = 1.8
Parameter values = .373 .343 .487 .590 .0610 .0819 .1073 .1045

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Residuals** | | | | |
| 4 | –.008 | –.220 | –.081 | –.147 | –.226 | –.201 | .157 | 1.147 |
| 5 | –.008 | –.052 | –.093 | .055 | .025 | –.072 | –.095 | –.007 |
| 6 | –.025 | –.063 | –.132 | –.187 | .045 | .133 | –.349 | .107 |
| 7 | .044 | –.178 | .047 | –.044 | –.164 | –.103 | –.138 | –.031 |

*Iteration #2,*
Residual sum of squares = 1.4
Parameter values = .295 .296 .488 .744 .0628 .0812 .1093 .1121

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Residuals** | | | | |
| 4 | –.019 | –.222 | –.107 | –.172 | –.177 | –.229 | .015 | .934 |
| 5 | .011 | –.024 | –.057 | .065 | .037 | .019 | –.085 | –.121 |
| 6 | –.034 | –.067 | –.128 | –.173 | .030 | .119 | –.260 | .091 |
| 7 | –.014 | –.233 | –.004 | –.084 | –.188 | –.167 | –.200 | .061 |

*Iteration, #13,*
Residual sum of squares = 0.3
Parameter values= .088 .288 .481 .731 .0546 .0793 .1034 .1007

| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Residuals** | | | | |
| 4 | .117 | –.082 | .012 | –.062 | –.044 | –.100 | .131 | –.007 |
| 5 | .034 | –.001 | –.030 | .070 | .032 | .038 | –.070 | –.120 |
| 6 | .018 | –.015 | –.074 | –.115 | .061 | .137 | –.212 | .134 |
| 7 | .087 | –.133 | .097 | .019 | –.080 | –.096 | –.150 | .156 |

Table 27 contains the numbers and F at age estimated by ADAPT. Except for 1983, the values are quite close to the true values (Table 9). No attempt was made to optimize the performance of ADAPT; other parameterizations might have performed better. For example, instead of fitting the Fs in the terminal year the Ns could be estimated directly. Other possibilities are that more or fewer Fs or qs might have fit the data better. The commercial catch rate or the effort could be included. ADAPT is a framework in which the imagination of the scientist can test a great range of formulations.

TABLE 26. Standard ADAPT diagnostics for data in Tables 9 and 14.

Approximate statistics assuming linearity near solution

Mean square residual ....... 0.011855

| Age | PAR. EST | STD. ERR | CV % | T | BIAS % |
|---|---|---|---|---|---|
| | | **Terminal year F** | | | |
| 4 | 0.087661 | 0.011241 | 12.82 | 7.80 | −7.48 |
| 5 | 0.288181 | 0.030471 | 10.57 | 9.46 | −9.73 |
| 6 | 0.480590 | 0.053846 | 11.20 | 8.93 | −12.85 |
| 7 | 0.731451 | 0.104135 | 14.24 | 7.02 | −19.16 |
| | | **Survey data q** | | | |
| 4 | 0.054632 | 0.002738 | 5.01 | 19.95 | −7.34 |
| 5 | 0.079268 | 0.003649 | 4.60 | 21.72 | −8.03 |
| 6 | 0.103358 | 0.004689 | 4.54 | 22.04 | −8.76 |
| 7 | 0.100666 | 0.004673 | 4.64 | 21.54 | −10.42 |

TABLE 27. Estimates of population size and fishing mortality from ADAPT.

| | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 |
| | | | | **Numbers** | | | | |
| 3 | 994 | 995 | 1 976 | 1 879 | 1 001 | 1 032 | 1 025 | 927 |
| 4 | 767 | 798 | 802 | 1 594 | 1 506 | 803 | 825 | 819 |
| 5 | 549 | 591 | 624 | 628 | 1 228 | 1 156 | 610 | 628 |
| 6 | 319 | 367 | 416 | 439 | 420 | 820 | 721 | 388 |
| 7 | 200 | 189 | 236 | 267 | 260 | 248 | 444 | 376 |
| 8 | 75 | 109 | 114 | 142 | 145 | 141 | 121 | 215 |
| 9 | 89 | 41 | 66 | 69 | 77 | 79 | 68 | 59 |
| | | | | **F** | | | | |
| 3 | .020 | .015 | .015 | .021 | .020 | .024 | .024 | .032 |
| 4 | .060 | .045 | .045 | .061 | .064 | .075 | .073 | .088 |
| 5 | .202 | .151 | .152 | .202 | .204 | .272 | .252 | .288 |
| 6 | .323 | .243 | .243 | .326 | .326 | .413 | .452 | .481 |
| 7 | .405 | .304 | .305 | .409 | .411 | .516 | .527 | .731 |
| 8 | .406 | .305 | .306 | .410 | .413 | .523 | .527 | .648 |
| 9 | .404 | .303 | .304 | .407 | .410 | .521 | .532 | .648 |

# V. Conclusions

The above examples were produced as a pedagogical set. They are not meant as a vehicle for comparing techniques. All three techniques, *ad hoc*, Laurec-Shepherd and ADAPT, performed very well, especially when compared to applications with real data. This is because the data were much less noisy than real data. Also, the data were stationary; q, M and the partial recruitment did not change over time. Furthermore, by using defined values for partial recruitment and M we had more information than would be available for a real fishery. Finally, the data were produced by the catch equation in a closed system.

Practical differences exist among the three tuning approaches that should be mentioned here. Because of its subjective nature, the *ad hoc* tuning technique is rarely advocated by working groups. The Laurec-Shepherd method is distributed as a 'canned' system of computer programs that cannot be modified. On the one hand this means that errors and bugs will not creep in and the performance is more or less assured. On the other hand it is not possible to alter it to meet a specific situation. ADAPT introduces an objective optimization that the *ad hoc* methods lack, and the choice of models is not constrained. In practice the models have been quite similar and resemble the example above. However, in order to maintain its versatility, ADAPT is susceptible to the introduction of errors.

Naturally, many topics were not covered in this review. Problems of stock migration and exploitation by more than one fleet are often encountered and special methods have been developed to handle them. There are also multispecies VPA which look at a number of species simultaneously.

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**User's Notes**

# VII. List of Participants

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**Annex 1**

# MAFF Directorate of Fisheries Research, Lowestoft

# Virtual Population Analysis: Version 3.0 (MSDOS/WINDOWS)

# User Guide*

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## Background

The programs within the Lowestoft VPA assessment suite have been designed for use in the analysis of fisheries population data. Each method estimates fishing mortality and numbers at age in a stock using data on international catches and natural mortality. The estimates can be 'tuned' to fleet catch data. Given the appropriate files, the program will calculate stock and spawning biomasses at the start of the year or spawning time.

This guide has been written as an aid to running the program. It provides summaries of the rationale underlying the techniques and of the algorithms used. For more detailed information the user is directed to documents referenced at the end of the text.

At certain points within the text, guidance notes are included, these provide suggestions for handling data and the procedures, or describe data related problems which may arise during a run.

* This is a transcript of the Working Paper presented for use at the Tutorial/Workshop.

## 0.1. PROGRAM HISTORY

Version 2.0 Initial Release of the DEC VAX implementation - December 1987.

Version 2.1 A major modification to the ***ad hoc*** tuning module allowing 20 fleets and 40 years of data. Each fleet may have a different first year of data. Extra summary statistics are produced in the report file. The aggregated methods option is removed. May 1988. Internal Report No. 13 describes the first stage of the program's development on the Lowestoft HP1000 computer. The transfer of the program to the DEC VAX 8200 mini-computer provided the opportunity to correct known bugs and carry out some enhancements.

Version 3.0 Code modified to run on IBM compatible PCs. September 1992. Two major changes have been made to previous versions of the program:

1) The program only handles single sex (unsexed) data.
2) The assessment methods now include Extended Survivors Analysis.

## 0.2 INSTALLATION OF THE VPA 3.0 SUITE

Two versions of VPA 3.0 are included on the software disk:

VPADOS, designed to operate within a DOS operating system environment (e.g. MSDOS, DRDOS). It requires 478k of conventional memory and can therefore be used within the 1 megabyte of memory available within older PCs.

VPAWIN, compiled to utilise the greater memory capacity available on newer PCs using Microsoft Windows versions 3.0 and later. Windows runs on the 80286/386/486 family of processors and requires at least 2 megabytes of extended memory. VPAWIN provides some of the features associated with the Windows graphics user interface, particularly the ability to access other applications during a VPA run. A maths coprocessor is not essential for running the programs, but does reduce computation times if present.

The following instructions will assume that the user wishes to run the program from the hard disk of their PC. The procedures are straightforward but if problems arise, consult the appropriate DOS or Windows manuals for the specific PC.

Both programs are installed by copying either VPADOS.EXE or VPAWIN.EXE and ASSESS.ICO from the floppy into the required hard disk working directory. When completed, VPADOS is ready for use.

The instructions for setting up VPAWIN within windows will assume that the user is familiar with the Windows environment and the <alt>/key or mouse procedures used to access menu bar options; these are described in detail in the Windows manuals.

On PCs without a mouse, open the Windows Applications window using the <alt> key procedures. From the Program Manager menu bar select File and New. Windows will open an application description window. The Type box should indicate a window item. Tab between boxes and type the program path and file name in the appropriate box. Enter a name for the program, the path of the directory to be the default for the data files and the icon file name (e.g. drive: \path \ASSESS.ICO). Tab to the OK button and press return. The application will be added to the group.

If using a mouse with windows, start File Manager and then open the Windows Applications window. Arrange the two windows so that they are adjacent. Within File Manager, place the mouse pointer on the VPAWIN.EXE file name. Press the mouse button and, keeping it depressed, drag the pointer to the Windows Applications window. Release the mouse button. Windows will create a new application using the VPAWIN program.

To customise the application interface, use the mouse to highlight the new VPAWIN application icon (click on it). Choose the File option from the Program Manager menu and then Properties. Set the name of the application and a directory for the application to start in. Choose the Icons button. In the box for the file name, type drive:\path\ASSESS.ICO or any other icon file name. Press return or click the OK button. Finally, the customised application is created by using the properties window OK button.

Note: If you set up a series of applications, each customised to use a separate start up directory, they can be used to provide immediate access to stock data directories. Once created an application icon can be copied by holding down the <Ctrl> key, clicking with the mouse on the icon, and with the mouse button held down, dragging the copy of the application to the required destination. The Properties of the application must then be edited to enter the new start up directory.

# 1. INTRODUCTION

The remainder of this guide provides information on data file requirements for the program and user input during an interactive run.

## 1.1 Constraints

The program imposes the following constraints on the data sets.

For the VPADOS program:

The maximum number of years is 30.
Ages must be in the range 0 to 20.
The maximum number of fleets is 10.

For the VPAWIN program:

The maximum number of years is 40.
Ages must be in the range 0 to 25.
The maximum number of fleets is 20.

In addition:

With one exception all data must be annual.
All data are single sex or unsexed.
References to years must use 4 digits.
The start of the year is January 1st.
Landings are in tonnes (t).
Numbers of fish are in thousands.
Fish weights at age are in kilograms (kg).

Note: In order to maintain compatibility with older data sets used in previous versions, the sex identifier has been retained in the data file structure. It is always set to 1.

The constraint that all data must be annual does not hold for the fleet catch data file; this will be described later. Data within this file may be obtained during short time periods e.g. seasonal catches.

## 1.2 Plus Group

The plus group is optional. It is adjustable during the interactive input to the program. If data is available for a greater range of ages than required in the current run, it is advantageous to create data files with all available age data and then customise the plus group dimensions during the user input.

## 1.3 Defaults

The program offers defaults, wherever possible, to assist and guide the user. These are set at commonly used or recommended choices. Thus, if in doubt, the user may generally accept the default offered as a sensible choice.

# 2. DATA FILE REQUIREMENTS

## 2.1 Overview

The program first opens and reads a user-defined Stock Index File. This a control file for the stock, and contains the main title, some control parameters, and the names of the data files to be read. (Sub-section 2.2 gives details of the required format). The positioning of file names within the index file is crucial to the correct operation of this program.

Reading of each data file is controlled by the data format identifier (DFI). Data file formats are given below, and a table defining the DFI options available is given in the Appendix section.

Note: Insufficient data in a data file will cause the program to stop, with an appropriate error message displayed on the screen. Too much data, i.e. extra values or an incorrect DFI, will not stop the program since excess values in a record or excess records in the file will be ignored. It is therefore important to specify the correct DFI. A visual check is provided by the program: whilst a data file is being read, a description of the format appears on the screen, together with the file title, file type identifier and contents description. Examples of data files are given below.

## 2.2 The Stock Index File

This file contains the names of the data files for one stock, and is the first file to be opened and read by the program.

File names within the index file should be prefixed by the drive:\path\ for the data directory or disk.

Note: The file positions are fundamental to the correct operation of this system. It is necessary to place the dummy file name **** in the relevant position(s) if one (or more) of the files is not available at the time that the index file is created.

The minimum requirements for a run are the catch at age and natural mortality files. These will allow a VPA or cohort analysis and a separable VPA to be performed. A fleet effort & catch data file is also required for *ad hoc* tuning or Extended Survivors Analysis (XSA). Table below contains a sample stock index file:

A. Index file contents Index No Notes

Stock title

< 80 characters
Sex option

Value 1 only
'Landings' file 1

Valid DOS format
'Catch numbers' file 2

Valid DOS format
'Catch weights' file 3

Valid DOS format
'Stock weights' file 4

Valid DOS format
'Natural mortality' file 5

Valid DOS format
'Proportion mature' file 6

Valid DOS format
'Proportion of F before spawning' file 7

Valid DOS format
'Proportion of M before spawning' file 8

Valid DOS format
'F on oldest age group by year' file 9

Valid DOS format
'F at age in last year' file 10

Valid DOS format
'Fleet tuning data' file 11

Optional

## 2.3 Data Files

### 2.3.1 Stock data files

The general format for each data file is as follows:

Title
Sex (only 1) Index No

First year Last year
First age Last age
DFI
Data (by age)
.
. (by year)
.
.
.
. ↓

The first and last year must be 4-digits and consistent through files 1-11.

Notes:

It is suggested that "title" should include species, ICES Division, file contents description, assessment working group and last amendment date, the maximum title length is 80 characters.

The DFI is treated independently for each file, so that the user can customise data input to data structures created by other programs.

Although both terminal F files (9,10) supply a common value (i.e. F on the oldest age in the last year), the program in practice makes use of that from file 10 only, the other is ignored (see examples).

### 2.3.2 Fleet data file

This data file is used to supply the fleet data needed for the *ad hoc* and XSA tuning modules. It has a different structure to the stock data files. The sex and effort codes have been retained for compatibility with old data sets. Both must be set to 1.

The data are presented by fleet and are constructed from effort and catch at age data.

The data file has to have the following structure:

Line number
Data
Comment

These are given as follows:

1.
File title
May be up to 80 characters.
2.
File type
MUST be 100 plus the number of fleets in the file. Max VPADOS=10
VPAWIN=20.
3.
Fleet name
May be up to 20 characters.
4.
First year, last year
Year range for this fleet (See note below).

Either 5(a). For *ad hoc* tuning
or 5(b). For XSA and *ad hoc* tuning

Sex code (1), effort code(1), alpha,beta

Sex code is:
1 only, unsexed or single.
Effort code is:
1 only, i.e. effort data present for this fleet
Alpha : start of fleet fishing period
Beta : end of fleet fishing period
6.
First age, last age
Age range for this fleet. (Note: last age is a true age; plus group data are not used in the tuning process.)
7.
Effort value, catch numbers at age
Line 7 is repeated for each year in the year range. The catch data are read across the age range given at line 6.

Lines 3 to 7 are repeated for each fleet present in the data file.

Alpha and beta indicate the start and finish of the fishing period within the year. They are given as fractions of a year, so that annual data would be entered with alpha = 0, beta = 1.0, second quarter effort would be alpha = 0.25, beta = 0.5.

There are differences in the fleet data files used for XSA and *ad hoc* tuning:

i) For *ad hoc* tuning all fleet catch data must have the same final year; the year for which terminal F predictions are to be made. When using Extended Survivors Analysis it is not necessary, but preferable, for all of the fleets catch data to be up to date.

ii) For Extended Survivors Analysis the use of the alpha and beta values enables seasonal or survey data to be handled correctly. The Extended Survivors Analysis data file can be used for *ad hoc* tuning, since the alpha and beta values will be ignored in the program.

## 2.4 Suggested File Naming Conventions

Standard formats for file names avoid the need for separate lists linking file names with particular stocks, and aid directory 'housekeeping'. e.g.

MAFF 3 character species code: See Appendix.

ICES Division: as two character division codes (4A, 4B etc.)
(Total sub-region: use nZ e.g. 4Z - North Sea.)

File contents:

LA - landings (tonnes whole)
CN - catch numbers at age (thousands)
CW - catch weights at age (kg)
SW - stock weights at age (kg)
NM - natural mortality
MO - maturity ogive
PF - Proportion of F before spawning
PM - Proportion of M before spawning
FO - F on oldest age in each year
FN - F at age in last year
TUN - Fleet catch and effort data

An example would be SOL7ECN.DAT which contains sole catch numbers from ICES division VIIe.

### 2.5 Interactive Responses

The program requires information to be supplied by the user during the run. Generally the required responses are either:

1) a data file name
2) a yes/no answer
3) a number, to select a menu option or supply a value.

Press Return/Enter after each answer.

Data file names and Yes/No responses may be given in upper or lower case, and Yes/No answers require only a single character.

If the file is not in either: (a) the directory entered in the Start up Directory box during the installation procedure, or (b) the directory containing the VPAWIN file; then file names should include the directory path e.g. drive: \path \filename.extension

If available, default responses are displayed (enclosed within < >) in the prompt for input. A default is taken by pressing the Return or Enter key only.

After completion of a run the Windows version of the program presents the user with a termination box. This allows two options, the closing of the window, or, keeping the window open with the screen output from the program displayed. The second option can be used to scroll back through the display to check input options. When finished the window is closed by the normal windows procedures.

## 3. RUNNING THE VPA SUITE

### 3.1 Starting the Program

To operate the DOS version, type VPADOS within the working directory, or, if the directory is within the PC environment path, any working directory.

There are several methods which can be used to run VPAWIN:

i) Within program manager, select File from the menu bar. Choose the Run option, and type the path for the working directory followed by VPAWIN.

ii) Within File Manager, select the working directory from the list of hard disk directories. Highlight the VPAWIN.EXE file name using the cursor or mouse. Press return, or double click the mouse.

iii) After installing the program as an application within a Windows group. Double click with the mouse on the VPA icon.

The last method is advised for quick/easy access to the application.

The windows version can be handled as a normal windows application with all the advantages of the multi-tasking graphics user interface. The application can be used full screen or within a window to allow concurrent access to text editors, spreadsheets etc. The main restriction to usage is that only one VPA can be opened or held minimised at any one time.

## 4. PROGRAM OVERVIEW

The first screen presents the program, the version number and describes the use of default options. At the foot of the screen is a prompt for input of the stock file name. If not in the current directory the path will be required.

The first part of the program reads the data files which define the stock being analysed. After the user has given the name of the Stock Index file, the program offers three options:

1) An option to read the first eight data files in the index file.
2) A fast option to read only the catch at age and natural mortality files for a quick run. This run will not produce the spawning stock and biomass information.
3) User prompts for input of each of the 8 data file names. The program offers the appropriate name from the index file list as a default. These files are opened and read in turn. This option is used if alternative data files are available.

Any inconsistent range parameters in files 1-8 will cause the program to stop and a screen table to be displayed enabling location of incorrect values. The remaining data files in the list are opened and read, if required, later in the program.

### 4.2 Year and Age Range Selection

The user is asked for the range of years and ages over which the analysis is to be performed. These can be a subset of the years and ages entered within the data files (the defaults). The only condition imposed by the program is that the youngest age in the data files is the youngest age for the run.

After selection of the oldest age for the subset, the user must inform the program whether it is to be a plus group. If it is, and the oldest age selected by the user is lower than the oldest age in the data files, the user selected age and all older ages are summed to form a new plus group. The catch, stock weights and other data attributes are adjusted to the new range.

## 4.3 Definition of Averages for the Main Output Tables

User defined averages are set for:

a) the fishing mortality table, and

b) the stock number table.

Averages are defined over a series of years or ages and, with some restrictions, can be unweighted or weighted. Defaults are listed under option 4 (Help). The settings are similar to those regularly used at North Sea Working Groups.

a) The fishing mortality table:

Three averages may be defined for the year (columns) means of the fishing mortality table. The first average becomes a reference F and is used to generate the relative F table. Four calculation methods available:

i) Arithmetic mean weighted by catch number per recruit.(FBARC)

ii) Arithmetic mean weighted by catch/population number per recruit.(FBARP)

iii) Arithmetic mean unweighted.(FBAR)

iv) Exploitation pattern weighting.(FBARS)

FBARC and FBARP are described in Shepherd (1982), FBARS in REFERENCE. As the first average to be defined is used as a reference F for later tables, the choice is restricted to either (i) or (iii).

Two averages can be defined for the age groups (rows) in the output F table. These averages are also calculated for the relative F table. The averages are restricted to unweighted arithmetic means with the user defining the range of years over which they are calculated.

b) The stock number table:

Two averages are available for the age groups (rows) of the stock number table. They are either arithmetic or geometric unweighted means and can be calculated over a selected range of years.

## 4.4 Selection of the Assessment Method

The Central Menu, which is the next screen display, gives the user a choice of options. Options 1, 2 and 3 can be viewed as a way of determining terminal fishing mortalities for a final VPA. Option 4 provides Extended Survivors Analysis, an alternative assessment method. This section is cyclical. Once a selected option has been completed the menu is re-displayed and the user prompted to select another option.

Note: In order to produce results option 9 must be chosen after each assessment. If not, the next assessment (if chosen) will overwrite the arrays.

### 4.4.1 Traditional VPA & cohort analysis

### Description of the method

The methods are 'traditional' in the sense that the user must supply values for terminal F. See Appendix.

## Using the method

Selection of option 1 at the central menu results in the presentation of two sub-menus to control the supply of terminal F values.

The first sub-menu offers the user four options to supply the F values for the oldest age for each year.

1) supplied from a data file (default file name taken from the index file),
2) interactively supplied by the user,
3) left unchanged from the previous run
4) as a user defined average of one or more younger F values.

**WARNING**:

There is an automatic zero catch adjustment in the program. If, for a given cohort, the catch of the oldest age group is zero, the program will move on to the next youngest age group and continue searching the cohort until a non-zero catch is found. Since the terminal F has been supplied for the oldest age of a particular cohort, then that value may be inappropriate if there are several zero catches. If this is found to be the case, then either amend the relevant value in the terminal F file (9 or 10), or adjust the value interactively for a re-run.

The second sub-menu offers the user three options to supply F values for each age in the most recent year. The values may be supplied using the methods (1) - (3) described above.

Finally the user must select either a full VPA or a cohort analysis. This is normally the final input required when using the 'traditional' methods.

### Results

This method produces no output directly. The results of the VPA should be printed or written to a file by selecting option 9 from the central menu. See below for a description of tables available.

## 4.4.2 Separable VPA

## Description of method

The method of separable VPA is described by Pope and Shepherd (1982) and is implemented in this system with the inclusion of a method of weighting the residuals as described by Stevens (1984).

The method determines values of fishing mortality from a (full) matrix of catch-at-age data, assuming a constant exploitation pattern.

The user has to specify a 'reference age' (which should be an age close to the age group contributing most catch in number) and one or more values of

a) terminal fishing mortality, i.e. F on the reference age in the last year
b) terminal selection, i.e. S on the oldest separate age-group, which is the fishing mortality relative to that on the reference age (on average).

The method then 'fills in' all the other fishing mortalities subject to these constraints. It does not use any information which is not available to a traditional VPA, but, given the starting assumptions ( i.e. M, terminal F, and terminal S), merely automates the procedure of generating an 'internally consistent' VPA, assuming a constant exploitation pattern.

The user is encouraged to generate VPAs for a range of values for terminal F and terminal S. Generally speaking one finds that the solutions are equally good interpretations of the data (as judged by the badness-of-fit parameter SSQ). Users should be aware that the method does not provide magic answers to their problems. On the contrary, it will present them with a range of solutions among which they need to choose, using additional information (e.g. effort data, egg survey results, ground fish survey data, prejudices about exploitation patterns, etc.).

Its virtue is that it automatically and objectively does what a skilled analyst might do by hand, whilst clearly identifying the assumptions made, and forcing one to think about the existence (or not) of evidence for or against the many possible interpretations of the catch-at-age data.

There is generally no virtue in using a larger array of data than is really necessary. The use of a long time series of data may be disadvantageous as the exploitation pattern may have changed through time. The weighting of year ratios should be used to pick out the range of years that the user wishes to contribute most to the selection pattern. This should be done by down-weighting the other years. Probably five to ten of the most recent years of reliable data is enough, and the program offers the last six years as a default. See Appendix for a more detailed description of the weighting methods.

Poor data for some age groups can cause a poor fit. The 'automatic' weighting of age ratios will down-weight the effect of such age ratios on the full exploited fishing mortality. However, the user can 'remove' age ratios (if so desired), by specifying manual weighting when prompted, and giving a value close to zero for those age groups.

## Using the method

The method is selected by choosing option 2 from the central menu.

The first section of the method defines the weightings to be given to the log catch ratios. These are the products of an age ratio weight and year ratio weight.

The year ratio weights, entered manually, should be chosen so that heaviest weighted time span best meets the assumption of a constant pattern. The program offers a default range of the last six years. The age ratio weights may be entered manually or calculated by the program. See Appendix for a more detailed description.

The next section requires the user to supply the age for unit selection, the number of terminal Fs and their values, the number of terminal Ss and their values. Each terminal F/terminal S combination will produce a separable solution. A maximum of 3 terminal Fs and 3 terminal Ss are allowed.

Next the user chooses where to have the separable F and stock number tables printed.

If only 1 terminal F and 1 terminal S have been chosen the user may choose to run a VPA or cohort analysis using separable stock numbers to give terminal F values.

Results

The separable method always produces output which is independent of option 9 on the central menu. File or printed output is available, consisting of:

1. Title, time and date of run, the year and age range of the data and the terminal F and S value for this run.

2. The initial and final sum of squared unweighted residuals and the number of iterations taken to reach the solution. The maximum number of iterations allowed is currently 150 and there is no option for the user to change this value.

3. The matrix of residuals showing the difference between the observed log catch ratio and the estimated log catch ratio. Row and column totals of weighted residuals are given - these should be all close to zero. The row and column weights are printed as is the sum of unweighted residuals.

4. F residuals (Fsep - Fvpa)

5. The fully exploited fishing mortality F for each year and the exploitation pattern S for each age.

6. If the user chose the output option, the separable F and population matrices.

If the user has run a VPA or cohort analysis, option 9 should be selected from the central menu to output the results.

### 4.4.3 *Ad hoc* VPA tuning

## Description of method

Descriptions of a variety of different methods are given by Pope and Shepherd (1985). Many of these methods were originally presented at ICES working group meetings and since that date further enhancements have been produced at such meetings. In this program, two tuning methods are available, Laurec-Shepherd and Hybrid.

Using fleet catch-at-age and effort data the methods generate estimates of fishing mortality for the most recent year. The user needs to define how the fishing mortalities for the oldest age group are derived. Note that these oldest age F values may have a major effect on the estimated Fs and hence populations in earlier years.

The tuning procedure involves a number of iterations, each consisting of a VPA (using the most recent terminal F values) followed by calculation of catchability values, a linear regression of catchability against time and prediction of new terminal F values in the most recent year. After a solution is achieved, a VPA or cohort analysis is carried out with the last set of estimated F values.

## Using the method

The method is selected using option 3 at the central menu.

In the first section of the program the user supplies the name of the fleet disaggregated data file, the name of a tuning summary report file and the tuning fleet year range to be used.

Next the user defines the weights to be applied to the data time series. The weights are applied to the Hybrid regressions and the constant catchability model. If weights are to be applied the user needs to supply the weights or choose one of the weighting functions available. See Appendix.

Terminal F values are then defined for the oldest age for each year being tuned. These values may be taken from a data file (default being the file name given in the index file), supplied interactively, or calculated on each iteration as the ratio of an average of some of the preceding ages for each year. If the age range defined in the data files or selected by the user is greater than the range of ages in the tuning data file, the program will prompt the user to input terminal F values for the missing ages. These may be entered at the keyboard or from a data file.

The user then selects the method to be used for the tuning.

1. Modified Hybrid: fits a time trend in q for one or more fleets. To ensure stability at least one fleet must have constant catchability. (Actually a mixed Hybrid+Laurec Shepherd method and not recommended for single fleet data sets.)
2. Laurec-Shepherd: uses mean q (no trend) for each fleet.

The tuning module uses a weighted mean to produce the estimated total fishing mortality. The estimated fishing mortality for each fleet is multiplied by the reciprocal of the prediction variance. These weighted mortalities are summed and the total is divided by the sum of the reciprocal variances.

The weighted means can be shrunk to an arithmetic mean of the population Fs, for that age, during the last five years of the data range. The F values used in the shrinkage mean are derived from the VPA of the previous iteration.

The user must supply a weight for the arithmetic mean of the Fs values during the last 5 years. This will be used for all ages. The weight is entered by the user as a standard error. A value of 0.2 is suggested as a starting point.

Note: If this option is required, raw Log catchability standard errors can be examined in a diagnostics file produced by running tuning without the shrinkage option. An appropriate value for weighting the average can then be entered during a repeat run.

The rationale behind shrinkage is described in Anon (1991), it can be used to remove bias in the estimates of fishing mortality and population abundance. Providing a conservative (restrained) estimate of the values.

Termination of the tuning process occurs when:

$$_{a}\left( F_{a,y,i} - F_{a,y,(i-1)} \right) \qquad < 0.0001$$

where a indicates age classes, y the final year and i iterations.

This is the sum ( across age groups ) of the absolute, final year, F value residuals between iterations. If the routine has not converged after 10 iterations the program will require confirmation that the user wishes to continue for a further 10 iterations. This should continue until convergence, or the user stops the tuning.

Note: Some data sets may not reach an optimal solution before generating extremely low (zero) values of F. If this occurs the program may fail when calculating subsequent outputs.

The tuned terminal F values are used to run a VPA or cohort analysis and a tuning report is prepared within the output file specified at the start of the method.

## Results

It is necessary to select option 9 from the central menu, in order to output the results of the VPA or cohort analysis generated using the terminal F values obtained by tuning.

The tuning summary report file will contain the stock title and the options selected to define the method, a table of the fishing mortality resulting from the final VPA and, the fleet catchability residuals, means and regression statistics for each age.

The catchability residuals should be plotted and examined for the presence of trends in catchability.

## 4.4 Extended Survivors Analysis (XSA)

*Ad hoc* methods for tuning single species VPAs to fleet catch data are sensitive to observation errors in the data for the final year (which is assumed to be exact). They fail to utilise the year-class strength information contained within the disaggregated catch data. Extended Survivors Analysis (XSA), (Shepherd, 1992), an extension of Survivors Analysis (Doubleday, 1981), provides an alternative method which overcomes these deficiencies. Shepherd (1992) discusses the derivation of the method.

## Description of the method

CPUE indices from each fleet are assumed to be related to the population abundance by a constant catchability model. The alpha and beta values supplied in the data files are used by XSA to convert CPUE from the period when fishing was prosecuted to the beginning of the year. These values are used with fleet catchabilities to derive fleet based population estimates ($P_{est}$) for each age and year (at the beginning of a year).

The method assumes that the population values derived from the VPA ($P_{vpa}$) are exact and that the fleet values of $P_{est}$ are estimates of them. For each cohort in the population array the fleet estimated $P_{est}$ values are used to produce a weighted estimate of the number of survivors present at the end of the final year or oldest age for that cohort. The survivors are then used, within a rearranged cohort analysis equation, to calculate new $P_{vpa}$ populations. Population values are used to derive new estimates of total and fishing mortality and fleet catchabilities. The process iterates until achieving the convergence criteria described for *ad hoc* tuning.

Various options for time series weighting, prior fleet weighting and exclusion of estimates with high standard errors are available. The RCT3/RCRTINX2 procedure (Shepherd, 1990), which allows the CPUE of recruiting age classes to be non-linearly proportional to year-class strength, can be used to analyse the younger ages.

## Using the method

The method is selected using option 4 of the central menu. The user supplies the name of the fleet tuning data file, the name of an output file for XSA tuning diagnostics and the range of years to be read from the data file for use in tuning.

The next section determines the characteristics of the tuning run.

The first option relates to the handling of the partially recruited ages within the data. It allows for the possibility that the catchability of younger age classes is in some way **dependent** on their abundance. The method of analysis has been used within the RCTINX2/RCT3 recruitment estimation program developed at Lowestoft, and is described in Shepherd (1992). For each fleet Log CPUE is linearly regressed against Log $P_{vpa}$. The relationship is used to predict $P_{est}$ values. The user must enter the first age at which catchability becomes **independent** of year-class strength.

It is known that methods such as *ad hoc* tuning and XSA are inherently unstable if the fishing mortality or catchability on the oldest true age class is not constrained to levels related to preceding ages. In *ad hoc* tuning this is achieved by using fixed terminal F values for the cohorts, or by calculating F on the oldest true age from a ratio of the average of n younger ages. Within XSA stability is achieved by setting the catchability of the oldest ages to be equal to a younger age. The age range can be adjusted by the user with the constraint that at least the oldest age must have its catchability fixed to that of the age below it.

The program presents the user with a screen illustrating the default settings for the calculations used within the XSA algorithm. These are derived from commonly used working group options. If these are suitable pressing return or answering N/n will skip over the following settings.

A Y/y answer will allow the user to select the following options:

The first series of questions describe the time series weighting to be applied to the data. Four options defining the taper type are available and these can be applied over a range of years. Appendix describes the weighting functions.

If the catchability of younger age classes is to be treated as dependent on the year-class strength, the type of the regression to be used in the analysis must be selected. The recommended options are C - calibration and P - predictive (F - functional has been included but is not illustrated). The minimum number of points required for a regression to be performed on a fleet data set must be entered.

The next option relates to the shrinkage of the survivor estimates. Survivor estimates derived from the combined fleet population estimates can be shrunk towards an average of n preceding years for a given age class in the terminal year, or an average of n younger ages for the survivors in the oldest age of earlier years. The number of years or ages to be used in the shrinkage mean can be customised to the dimensions of the data set being studied.

The program requires a value for the weight to be applied to the mean. This weight is similar to that for the *ad hoc* tuning and are the variances of the Log reciprocal catchability.

The user is asked whether they wish to exclude fleets with very low standard errors about the mean of Log reciprocal catchability. These would receive high weights in the combined terminal population calculations. The option is designed to reduce the effects of few data points with a very good fit. If selected a standard error (s.e.) threshold (cut-off value) must be entered. Within the weighted estimation of survivor populations, the value is substituted for the weight of ages with a lower standard error than the threshold.

Note: An examination of the output from an XSA diagnostics file produced without shrinkage or the above option (cut-off) will give an indication of the magnitude of the s.e. present within the data. Data sets have been tested for which the use of the cut-off option has down weighted fleets with very low s.e. and resulted in convergence that could not otherwise have been achieved.

The final user selected option will only be available if more than one tuning fleet is present in the data file. This allows additional weights to be attached to fleet estimates when calculating the survivor populations. Weights are in the range: 0.0-1.0.

After completion of the user input the program runs until convergence if not achieved after 30 iterations the program will request clearance for additional iterations repeated in blocks of 10.

On convergence or user termination of the iterations the program writes a diagnostic file and returns to the main menu to allow output of the population statistics tables.

## Results

It is necessary to select option 9 from the central menu, in order to output the results of the VPA or cohort analysis generated using the terminal F values obtained.

The XSA report file will contain the stock title, run time and data file name. This is followed by a listing of the user options defining the method and the number of iterations performed to reach convergence.

Tables of F at age and estimated population size for the last 15 years of the time series are written to the file. The population estimates include the survivors at the end of the final year. For each fleet Log catchability residuals at age and mean catchability with their standard error are listed.

Note: The regression algorithm used within XSA is designed to handle missing or zero fleet catch data efficiently (missing data are weighted out of the analysis). At present this is not the case for *ad hoc* tuning, in which zero values in the catch data are replaced by a very small catch ( 1/10th of the smallest fleet catch). This produces very low catchability values for *ad hoc* tuning which will not be present in an XSA output.

## 4.5 Selection of Output

Selection of option 9 from the central menu will display a menu showing the 17 different tables available.

Tables 1 to 7 may be printed at any time and give data read into the program from the stock data files. Using code 18 will produce all 7 tables.

Tables 8 to 17 can be produced after running a VPA in one of the options 1, 2, 3 or 4 from the central menu. The results from a pass through one of those methods should be printed before reselecting any of those options or before selecting option 0 to stop the program. Using code 19 will produce all 10 results tables.

Average fishing mortalities and stock numbers defined by the user will appear on the corresponding tables.

Selection of summary Table 16 and/or 17 will also produce Table 8 - Fishing Mortality and Table 10 - Stock Number.

Example shows the list of tables as they appear on the screen.

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# 6. APPENDIX

A.1 VPA/cohort analysis algorithms.
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A.3 Weighting methods.
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# Appendix A.1 VPA/Cohort Analysis Algorithms

## Cohort Analysis

This option uses J. G. Pope's cohort approximation to estimate the previous population:

$$N e^{m} * N_{t+1} + e^{m/2} * Ct \quad (1)$$

and for the corresponding total and fishing mortalities:

$$Z_t = 1n \quad (2)$$

$$F_t = Z_t - M_t \quad (3)$$

## Traditional VPA

The VPA equation is

$$= (). \quad (4)$$

Given $C_t$ and $N_{t+1}$, the problem is to find $F_t$ that solves the equation.

This can be conveniently done by writing the equation as:

$$Y = e^{-Z_t} * - (1 - e^{-Z_t}) \quad (5)$$

and finding the value of $F_t$ for which Y is zero.

First estimates of $F_t$ are obtained from cohort analysis and refined using an approximation to the Newton-Raphson method (J. G. Pope - personal communication). This gives fresh estimates of $F_t$ as

$$F_t(new) = F_t(old) - \quad (6)$$

This is simplified by using the cohort approximation for the catch equation which gives:

$$= -e^{-F_t} * G \qquad (7)$$

where G = $e^{-3m/2}$ * .

Iteration using equations 5 and 6 continues until I Y I £0.0001.

This gives estimates of $F_t$ which satisfy the equation with a precision of

$$\pm 0.0001\ e^{m/2}.$$

## Appendix A.2

Shepherd (1992) discusses the least squares derivation of XSA. CPUE indices from each fleet are assumed to be related to the population abundance by the constant catchability model

$$U_{(yaf)} = q_{(af)} A_{(yaf)} P_{(ya)} \quad (1)$$

where y indexes year, a age and f fleet. A is an averaging factor relating the population during the time at which the catch was taken to the population at the beginning of the year P. A is given by:

$$A(yaf) = \frac{e^{gZ} - e^{-hZ}}{(h-g)Z} \quad (2)$$

where g is the start of the period of fishing and h the end (both expressed as fractions of a year). In practice XSA corrects the CPUE to the beginning of the year.

$$U'_{(yaf)} = U_{(yaf)} / A_{(yaf)} \quad (3)$$

Population estimates at the beginning of a year are derived from each fleet.

$$P_{est(yaf)} = U'_{(yaf)} / q_{(af)} \quad (4)$$

The method assumes that the population values derived from the VPA ($P_{vpa}$) are exact and that the values of $P_{est}$ are estimates of these values. Shepherd (1992) shows that by a rearrangement of Pope's cohort equation the VPA population for age a in year y is given by:

$$P_{vpa(ya)} = ECM_{(ya)} P_{t(k)} + P_{c(ya)} \quad (5)$$

ECM is the exponential cumulative natural mortality summed from the greatest cohort age back through the cohort to (y,a). $P_{t(k)}$ is the terminal population (survivors) at the end of the final year or oldest cohort true age and $P_c$ is given by:

$$P_{c(ya)} = sum_i [ ECM_i C_i e^{-0.5Mi} ] \quad (6)$$

'$sum_i$' describes summation backwards up the cohort from the oldest cohort age to the (y,a) population. $P_c$ therefore describes the contribution of the raised accumulated catches to the population in year (y,a). Within the traditional VPA and cohort analyses or one iteration of MSVPA, M , $C_i$ and therefore $P_c$ are constant. Shepherd (1992) derives the log of reciprocal catchability (1/q) used to calculate the $P_{est}$ values using equation (4) by:

$$Ln[ 1/q_{(af)} ] = sum_y [ Ln(P_{vpa(ya)} / U'_{(yaf)} / 2_{(af)} ] / sum_y [ 1/2_{(af)} ] \quad (7)$$

where $2_{(a,f)}$ is the variance of the CPUE data. Finally the cohort terminal populations are estimated by:

$$LnP_t = sum_f sum_i [\, w'(LnP_{est} - CUMZ)] \,/\, sum_f sum_i [\, w'] \qquad (8)$$

and w' = w/ ECF

This is a weighted geometric mean over all available data for the cohort estimated from the CPUE data reduced by total mortality to the end of the final year. The division by ECF progressively reduces the weight of the younger ages of the cohort. Within the XSA algorithm the w values are the variance of the log reciprocal catchability. Calculation of catchability and the terminal populations is an iterative process with new $P_{vpa}$ values generated at each iteration.

## Appendix A.3

## Weighting

### 3.1. Separable VPA

The main assumption of Separable VPA is that the selection pattern is constant. The year ratio weighting allows the user to limit the analysis to recent years where the selection pattern is most likely to have remained approximately constant.

The age ratio weighting can be used to moderate the effect of poorly sampled age groups upon the fishing pattern. The option of generating these weights automatically by taking into account the variance of the residuals in each age group gives an alternative. These automatic weights will normally be lowest on the younger and older age groups. Very low weights associated with low selection values on the younger age groups may suggest that there is no major reason to include them in the analysis at all. Similarly low weights on older age groups may suggest that lowering the plus group age could be worthwhile.

### 3.2. Time Series Weighting

The module will offer either (1) no weighting of the regressions, (2) weights supplied by the user for each year or (3) a weighting function. The latter assigns each year a weight which depends on its difference in time from the prediction year.

| | | | |
|---|---|---|---|
| So | $W_y$ | = | $(1^{-m})^m$ |
| where | $W_y$ | = | Weight for year y |
| | $d_y$ | = | Prediction year - y |
| | $D_y$ | = | Prediction year - first tuned year + 1 |
| | m | = | 1, 2 or 3 giving linear taper, biquadratic or tricubic weights respectively |

The regression weights used are printed in the report file of the tuning module.

## Data Format Identifier (DFI)

This parameter informs the program of the data format in a file. Valid parameters and their respective data formats are:

| DFI | Expected data format |
|---|---|
| 1 | data data data<br>data<br>data<br>etc<br><br>i.e. an array of ages → by year ↓. |
| 2 | data data data<br><br>i.e. a row vector for data by age. |

3 data

i.e. a scalar value.

4 No data expected.

5 data
data
data
●
●
i.e. a column vector for data by year.

Spaces or commas are standard separators.

The table below defines the valid use of each DFI within the data files.

Data file#
DFI

1
2
3
4
5

Array
Row
Scalar
None
Column
1 (Landings)

√
2 (Catch numbers)
√

3 (Catch weights)
√
√

4 (Stock weights)
√
√

√

5 (Natural mortality)
√
√
√

√
6 (Maturity proportion)
√
√

7 (Prop. of F before sp.)
√
√
√

√
8 (Prop. of M before sp.)
√
√
√

√
9 (F on oldest age)

√
10 (F at age)

√

e.g. DFI 3 may only be used in data files #5, #7 and #8.

Failure to observe these requirements could result in either a program error message or a runtime error message being displayed on the terminal. In both cases the program will stop.

## Annex 2

# A Brief History of ADAPT*

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ADAPT is an age-structured, adaptable framework for estimating historical stock sizes of an exploited population. It is not a rigidly defined model in the mathematical sense, but rather a flexible set of modular tools designed to integrate all available data that may contain useful information on population size.

The statistical basis of the ADAPTive approach is to minimize the discrepancy between observations of state variables and their predicted values. The observed state variables are usually (but are not limited to) age-specific indices of population size, e.g. from commercial catch-effort data, research surveys, mark-recapture experiments, etc. The predicted values are a function of a vector of estimated population size (age-specific) and catchability parameters; and standard population dynamics equations (usually Gulland's (MS 1965) VPA). Nonlinear least squares objective functions are generally employed to minimize the discrepancies.

The appellation ADAPT was introduced by Gavaris (MS 1988). However, the foundation of the method was developed over the preceding decade under an umbrella of research generally referred to as VPA tuning. Although not generally recognized, Parks (1976) was the first to tune a VPA using auxiliary data and a least squares objective function. He tuned VPA back-calculated fishing mortality rates (Fs) to Fs derived independently from tagging experiments. Gray (MS 1977) suggested a least squares approach to estimate mortality rates (both F and M) using a commercial catch-per-unit-effort (CPUE) index of abundance as auxiliary data.

Doubleday (1981) used age-specific research survey indices of abundance as auxiliary data to estimate survivors in the terminal year for each cohort. This appears to have been the first attempt to utilize multiple indices of abundance in a least squares tuning procedure.

Parrack (1986) expanded upon Doubleday's work by integrating indices of abundance from widely diverse sources into the least squares objective function. His formulation allowed indices from commercial fisheries, research surveys, larval surveys, etc. Indices could be either age-specific or represent an age group; and could be expressed in either population number

* This is a transcript of the Working Paper presented for use at the Tutorial/Workshop.

or biomass. Indices were related to population size either linearly or through a power function. Variance estimates were made assuming linearity at the optimal solution. He also recognized that not all indices are of equal value in measuring population abundance. Some indices will always be inherently more variable than others, and some may be biased. he introduced detailed examination of residuals and correlation statistics as an acceptance/rejection filter that each index needed to pass through in order to be used in the final tuning. The tuning procedure described by Parrack (1986) is the kernel of the method today known as ADAPT, both in terms of the objective function employed and in terms of the underlying philosophy.

Gavariṡ (MS 1988) ADAPTive Framework generalized Parrack's procedure in several ways:

1) The adaptive aspects of the method were greatly enhanced through the use of a modular model structure and implementation in the APL programming language. This made it possible to modify the objective function significantly, as needed to rectify problems, even during the course of an assessment working group meeting.

2) A Marquardt algorithm (Bard, 1974) was used for optimization of the least squares objective function. This allowed the simultaneous estimation of age-specific population sizes in the terminal year and catchabilities (Parrack estimated only the full F in the terminal year and relied on an input partial recruitment vector to complete the terminal year F vector). Additionally, the use of numerical derivatives in the Marquardt algorithm greatly enhanced the adaptive philosophy by making objective function modifications easy to implement.

3) The more complete statistical model allowed for improved diagnostics. In addition to residual analysis, availability of the full variance-covariance matrix (assuming linearization at the optimal solution) provided variance estimates of all parameters, correlation among parameter estimates, and in general a better sense of which parameters were estimable from the available information.

The integration of many diverse sources of information focused attention on objective procedures to account for differences in the quality of information. Collie (1988) suggested that all indices of abundance should be included in the least squares objective function rather than employing Parrack's acceptance/rejective criteria. He recommended weighting the indices by the inverse of their variances. Vaughn *et al.* (1989) used Monte Carlo simulation to investigate the effect of weighting on the Fs estimated for bluefin tuna. They found that F estimates were unbiased only when the indices were weighted. Conser and Powers (1990) developed a more general weighting procedure that allowed for two-way effects, i.e. index and year. Gavaris and Van Eeckhaute (MS 1991) employed a similar weighting procedure using an analysis of variance approach. Gassuikov (1990) suggested an alternative approach to weighting in ADAPT using the moving check procedure of Vapnik (1982).

Other areas of current research on the ADAPTive method include:

1) balancing the number of parameters estimated with the need to impose some model structure, e.g. the assumption of a partial recruitment pattern (Conser and Powers, 1990; Restrepo and Powers, 1991);

2) procedures for incorporating all components of variance into the ADAPT variance estimates of stock size and fishing mortality (Restrepo *et al.*, 1991).

It is noteworthy that all of the above cited work (with the exception of Gray, MS 1977 and Gassuikov, MS 1990) was developed in conjunction with assessment working groups associated with either the International Commission for the Conservation of Atlantic Tunas (ICCAT) or the Canadian Atlantic Fishery Scientific Advisory Committee (CAFSAC). This development environment has been influential in shaping the flexibility and the pragmatic nature of ADAPT. It differs from the Doubleday-Deriso catch-at-age models (Doubleday, 1976; Deriso *et al.*, 1985; Kimura, 1989), developed over a similar period, in several ways. Although both employ least squares objective functions and tune to auxiliary data,

a) ADAPT does not assume separability (of fishing mortality and selectivity)
b) ADAPT is more parsimonious in the number of parameters estimated
c) ADAPT's philosophy requires careful attention to diagnostics (e.g. residuals, correlations, etc). This coupled with its flexibility (including objective function modifications), encourages iterative re-runs of the model and re-thinking some assumptions until all major problems are rectified.

ADAPT has been used for assessment of a wide variety of fish stocks in several different assessment arenas, e.g. ICCAT, CAFSAC, NAFO. A small sample of the extent of these applications is provided for interested readers: ICCAT (Conser, 1989; Nelson *et al.*, 1990), CAFSAC (O'Boyle *et al.*, MS 1988; Chouinard and Sinclair, MS 1988; Rivard, MS 1989); NAFO (Baird and Bishop, MS 1989); also see SEFC (1989); and many others.

Although beyond the scope of this discussion, it should be noted that over a similar period, many pragmatic VPA tuning methods were also developed in conjunction with the ICES Assessment Methods Working Group. These methods, generally called *ad hoc* tuning methods (c.f. Pope and Shepherd, 1985), differ from ADAPT and the Doubleday-Deriso models in that they do not have a formal statistical basis, i.e. they do not have an explicit objective function to be optimized. However, they appear to give satisfactory results for many of the stocks in the ICES arena.

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**Annex 3**

# FORTRAN Version of ADAPT Using Sample Data from NAFO Special Session Workbook*

by R. Mohn

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## PROGRAM FADAPT2 - MAC VERSION

```
C
C      FCREATE is a FORTRAN version of the ADAPT software developed in APL. It uses a
C      slighty modified Marquart procedure from the APL version. It also uses GAUSSJ from
C      the Numerical Recipes. The main program reads data set of catch at age (CDAT) and
C      abundance indices (ABDAT) from files cat.in and abund.in. The parameters to be fit are
C      the Fs and the Qs at age. Subroutine MODEL combines the data and parameters in a
C      cohort model to estimate the abundance data.

       INTEGER I, J
       DOUBLE PRECISION RSS
       INCLUDE ':FADAPT:fadapt2.inc'
C
C
       OPEN (28,FILE=':fadapt:inits.in')
       OPEN (29,FILE=':fadapt:cat.in')
       OPEN (30,FILE=':fadapt:abund.in')
C
       DO 5 I = 1, AGESZ
       DO 5 J = 1, YRSZ
       NMOD (I,J) = 0.0
       FMOD (I,J) = 0.0
       BIMOD (I,J) = 0.0
       ABMOD (I,J) = 0.0
       CDAT (I,J) = 0.0
       WDAT (I,J) = 0.0
       ABDAT (I,J) = 0.0
  5    CONTINUE
C
       READ (28,*) NA, NY
       READ (28,*) NAGFMOD, NAGQMOD
       NPARA = NAGFMOD + NAGQMOD
```

* This is a transcript of the Working Paper presented for use at the Tutorial/Workshop.

```
      NRESID = NAGQMOD * NY
      READ (28,*) M
      READ (28,*) (AGFMOD (I), I = 1,NAGFMOD)
      READ (28,*) (AGQMOD (I), I = 1,NAGQMOD)
      READ (28,*) (INITIAL (I), I = 1,NPARA)
      WRITE(*,*) 'NS AND INIT',NA,NY,(INITIAL(I), I = 1,NPARA)
      READ (28,*) (SELMOD (I), I = 1,NA)
      READ (28,*) (TERMOD (I), I = 1,NY)
      DO 10 I = 1, NA
      READ (29,*) (CDAT (I,J), J= 1, NY)
   10 CONTINUE
      DO 20 I = 1, NA
      READ (30,*) (ABDAT(I,J), J= 1, NY)
   20 CONTINUE
C      DO 30 I = 1, NA
C      READ (31,*) (WDAT(I,J), J= 1, NY)
C  30  CONTINUE
      WRITE (*,*) CDAT (NA,NY), ABDAT(NA,NY)
      CALL MODEL (INITIAL, RESID,RSS)
      CALL NLLS (INITIAL,PAR)
      WRITE (*,*) 'Finished'
      DO 100 I = 1, NA
      WRITE (*,101) I,(NMOD(I,J), J=1, NY)
  101 FORMAT (' N ',I3,10F8.0)
  100 CONTINUE
      DO 110 I = 1, NA
      WRITE (*,111) I, (FMOD(I,J),J=1, NY)
  111 FORMAT (' F ',I3,10F8.3)
  110 CONTINUE
      PAUSE
      STOP
      END
```

## SUBROUTINE MODEL (PAR,RESID,RSS)

```
C
C     MODEL is a VPA which uses terminal Fs at ages AGFMOD and qs at ages AGQMOD
C     to estimate the abundance data and returns the residual
C
      DOUBLE PRECISION Q(10), Z, FLY(10), AVSEL, AVFLY, RSS
      INTEGER I,J,K
      INCLUDE ':FADAPT:fadapt2,inc'
      SAVE
C
      AVSEL = 0.0
      AVFLY = 0.0
      DO 10 I = 1, NAGFMOD
      FLY(AGFMOD(I)) = PAR(I)
      AVFLY = AVFLY + PAR(I)/NAGFMOD
```

```
      AVSEL = AVSEL + SELMOD(AGFMOD(I))/NAGFMOD
   10 CONTINUE
      DO 15 I = 1, NAGQMOD
      Q(I) = PAR(NAGFMOD + I)
   15 CONTINUE
C
      DO 20 I = 1, NA
      IF((I .LT. AGFMOD(1)) . OR. (I .GT. AGFMOD(NAGFMOD))) THEN
        FLY(I) = SELMOD(I) * AVFLY/AVSEL
      END IF
      FMOD(I,NY) = FLY(I)
      Z = FLY(I) + M
      NMOD(I,NY) = CDAT(I,NY) * Z/(FLY(I) * (1-EXP(-Z)))
   20 CONTINUE
C
      DO 30 J= 1,NY
      FMOD(NA,J) = TERMOD(J)
      Z = M + TERMOD(J)
      NMOD(NA,J) = CDAT(NA,J) * Z/(TERMOD(J) * (1-EXP(-Z)))
   30 CONTINUE

C     Proceed back cohorts to find N's and F's
C
      DO 33 I = NA-1, 1, -1
      DO 33 J = NY-1, 1, -1
      NMOD(I, J) = (NMOD(I+1, J+1)*EXP(M)) +CDAT(I,J)*EXP(M/2.)
      FMOD(I,J) = LOG(NMOD(I,J)/NMOD(I+1,J=1)) - M
   33 CONTINUE
      K = 0
      RSS = 0.0
      DO 40I = 1, NAGQMOD
      DO 40 J = 1, NY
      ABMOD(AGQMOD(I),J) = NMOD(AGQMOD(I),J) * Q(I)
      K = K + 1
      RESID(K) = (LOG(1 + ABDAT(AGQMOD(I),J))) -
     1                   LOG(1 + ABMOD(AGQMOD(I),J))
      RSS = RSS + RESID(K)**2
   40 CONTINUE
C      DO 100 I = 1, NA
C      WRITE(*,101) (NMOD(I,J),J=1, NY)
  101 FORMAT (' N ',10F8.0)
  100 CONTINUE
      RETURN
      END
```

## SUBROUTINE DIFFMOD (PART,TDYDA)

```
C
C     Produce estimates of the derivatives of the model output with respect to the parameters
C     using the first divided difference.
```

```
C
      INTEGER NA,NY,NYMOD,NPARA,NRESID,NAGQMOD,NAGFMOD
      INTEGER I, J, PSZ, RSZ
      PARAMETER (RSZ = 50)
      PARAMETER (PSZ = 10)
      COMMON /SIZES/ NA, NY, NYMOD,NPARA,NRESID, NAGFMOD, NAGQMOD
      DOUBLE PRECISION TDYDA (RSZ,PSZ), RESREF (RSZ), STEP,
     1              RES(RSZ),PAR(PSZ), AA(RSZ),RSS
      SAVE

      CALL MODEL(PAR,RESREF,RSS)
      STEP = .001
      DO 10 I = 1, NPARA
            DO 20 J = 1, NPARA
            AA(J) = PAR(J)
            IF(J .EQ. I) AA(J) = PAR(J)*(1 + STEP)
   20       CONTINUE
      CALL MODEL(AA,RES,RSS)
      DO 40 J = 1, NRESID
      TDYDA(J,I) = (RESREF(J) = RES(J))/PAR(I)/STEP
   40 CONTINUE
   10 CONTINUE
      RETURN
      END
```

## SUBROUTINE NLLS (INITIAL,PAR)

```
C
C     Marquardt algorithm
C
      IMPLICIT NONE
      INTEGER I,12,J,K,INNER, INLIM, LIMIT,PSZ,RSZ
      INTEGER NA,NY,NYMOD,NPARA,NRESID,NAGQMOD,NAGFMOD
      PARAMETER (RSZ = 50)
      PARAMETER (PSZ = 10)
      DOUBLE PRECISION RSS, PHI, NPHI, TPAR(PSZ), INITIAL(PSZ),
     1       GRAD(PSZ), DE(RSZ,PSZ), HESS(PSZ,PSZ), NORM(PSZ).
     2       RESID(RSZ), PAR(PSZ), MSR, LAMBDA, TMAX, TEM
      LOGICAL FLAG
      COMMON /SIZES/ NA, NY, NYMOD,NPARA,NRESID, NAGFMOD, NAGQMOD
      CALL MODEL(INITIAL, RESID, RSS)
      PHI = RSS
      NPHI = RSS
      LAMBDA = 0.01
      LIMIT = 20
      INLIM = 10
      DO 10 I = 1, NPARA
   10       PAR(I) = INITIAL(I)
C
```

```
C       MAIN LOOP
C
        DO 100 J =1, LIMIT
        WRITE(*,91) ' OUTER ',J,PHI,(PAR(K),K=1,NPARA)
 91             FORMAT(A7, I4,9F8.4)
        DO 30 I = 1, NPARA
 30             TPAR(I) = PAR(I)
        PHI = NPHI
        CALL DIFFMOD(PAR,DE)
        DO 110 I = 1, NPARA
        GRAD(I) = 0.0
        DO 120 K = 1, NRESID
 120            GRAD(I) = GRAD(I) + 2*RESID(K)*DE(K,I)
 110            CONTINUE
        DO 200 I = 1, NPARA
        DO 200 I2 = 1, NPARA
        HESS(I,I2) = 0.0
        DO 220 K = 1, NRESID
 220            HESS(I,I2) = HESS(I,I2) + 2. * DE(K,I)*DE(K,I2)
 200            CONTINUE
        LAMBDA = LAMBDA * 0.1
        INNER = 1
        DO 250 I = 1, NPARA
        HESS(I,I) = HESS(I,I) * (1. + LAMBDA)
 250            CONTINUE
        DO 330 I = 1, NPARA
        NORM(I) = 0.0
        DO 300 K = 1, NPARA
 330            NORM(I) = NORM(I) + HESS(I,K)**2
 300            NORM(I) = SQRT(NORM(I))
        DO 350 I = 1, NPARA
        DO 350 K = 1, NPARA
        HESS(I,K) = HESS(I,K)/NORM(K)
 350            CONTINUE
        CALL GAUSSJ(HESS,NPARA,GRAD,1)
        DO 360 I = 1,NPARA
        GRAD(I) = GRAD(I) / NORM(I)
 360            CONTINUE
C- - -   NOTE GRAD NOW CONTAINS THE SOLUTION (VECTOR V IN APL VERSION)
        DO 380 I = 1,NPARA
 380            PAR(I) = TPAR(I) + GRAD(I)
        CALL FEASREG(PAR,FLAG)
        IF(.NOT. FLAG) GO TO 400
        CALL MODEL(PAR,RESID,RSS)
        NPHI = RSS
 96             FORMAT (' PHI, NPHI ',2F10.3)
        IF(PHI .GE. NPHI) GO TO 600
 400            LAMBDA = LAMBDA * 100
 500            DO 510 I = 1, NPARA
```

```
      GRAD(I) = GRAD(I)*0.1**INNER
      PAR(I) = TPAR(I) + GRAD(I)
510         CONTINUE
      INNER = INNER + 1
      IF(INLIM .LT. INNER) GO TO 600
      CALL FEASREG(PAR,FLAG)
      IF(.NOT. FLAG) GO TO 500
      CALL MODEL(PAR,RESID,RSS)
      NPHI = RSS
      IF(PHI .GE. NPHI) GO TO 600
      GO TO 500
600         CONTINUE
      IF(ABS((NPHI-PHI)/PHI) .LT. 0.0001) THEN
        WRITE(*,*)' RELATIVE CHANGE IN RESID SUM SQUARES .LT. 0.0001'
       RETURN
      ENDIF
      TMAX = 0.0
      DO 630 I = 1,NPARA
      TEM = ABS((PAR(I)-TPAR(I))/PAR(I))
      IF(TEM .GT. TMAX)     TMAX = TEM
630         CONTINUE
      IF(TMAX .LT. 0.00001) THEN
        WRITE(*,*) 'RELATIVE PARAMETER CHANGE .LT.0.00001'
       RETURN
      ENDIF
100         CONTINUE
      WRITE(*,*) 'MAIN LOOP LIMIT EXCEEDED'
      MSR = RSS/(NRESID - NPARA)
      RETURN
      END
```

## SUBROUTINE FEASREG(P,OK)

```
C
C     Checks that the parameters are in the feasible region.  In this example all the Fs and qs
C     must be positive.
C
      INTEGER NA, NY, NYMOD,NPARA,NRESID,NAGFMOD, NAGQMOD
      DOUBLE PRECISION P(20)
      LOGICAL OK
      COMMON /SIZES/ NA, NY, NYMOD,NPARA,NRESID,NAGFMOD, NAGQMOD

      OK = .TRUE.
      DO 10 I = 1, NPARA
      IF(P(I) .LE. 0.0) OK = .FALSE.
10          CONTINUE
      RETURN
      END
```

## SUBROUTINE GAUSSJ (A,N,TQ,M)

```
C
C      Solves set of linear equations by Gauss-Jordan method
C
       INTEGER I,J, L, LL, K, N, M, PSZ
       PARAMETER (PSZ = 10)
       DOUBLE PRECISION A(PSZ,PSZ),B(PSZ,1), BIG, DUM, PIVINV,
     1              TQ(PSZ)
       INTEGER IPIV(PSZ),INDXR(PSZ),INDXC(PSZ), IROW,ICOL
      `SAVE
       DO 10 I = 1,N
 10         B(1,1) = TQ(I)
       DO 11 J=1,N
          IPIV(J)=0
 11         CONTINUE
       DO 22 I=1,N
          BIG=0.
          DO 13 J=1,N
            IF(IPIV(J).NE.1) THEN
              DO 12 K=1,N
                IF (IPIV(K).EQ.0) THEN
                  IF (ABS(A(J,K)).GE.BIG) THEN
                    BIG=ABS(A(J,K))
                    IROW=J
                    ICOL=K
                  ENDIF
                ELSE IF (IPIV(K).GT.1) THEN
                  PAUSE 'Singular matrix'
                ENDIF
 12               CONTINUE
           ENDIF
 13           CONTINUE
         IPIV(ICOL)=IPIV(ICOL)+1
         IF (IROW.NE.ICOL) THEN
           DO 14 L=1,N
             DUM=A(IROW,L)
             A(IROW,L)=A(ICOL,L)
             A(ICOL,L)=DUM
 14             CONTINUE
           DO 15 L=1,M
             DUM=B(IROW,L)
             B(IROW,L)=B(ICOL,L)
             B(ICOL,L)=DUM
 15             CONTINUE
         ENDIF
         INDXR(I)=IROW
         INDXC(I)=ICOL
         IF (A(ICOL,ICOL).EQ.0.) PAUSE 'Singular matrix.'
```

```
      PIVINV=1/A(ICOL,ICOL)
      A(ICOL,ICOL)=1.
      DO 16 L=1,N
        A(ICOL,L)=A(ICOL,L)*PIVINV
16        CONTINUE
      DO 17 L=1,M
        B(ICOL,L)=B(ICOL,L)*PIVINV
17        CONTINUE
      DO 21 LL=1,N
        IF(LL.NE.ICOL) THEN
          DUM=A(LL,ICOL)
          A(LL,ICOL)=0.
          DO 18 L=1,N
            A(LL,L)=A(LL,L)-A(ICOL,L)*DUM
18            CONTINUE
          DO 19 L=1,M
            B(LL,L)=B(LL,L)-B(ICOL,L)*DUM
19            CONTINUE
        ENDIF
21          CONTINUE
22        CONTINUE
    DO 24 L=N,1,-1
      IF(INDXR(L).NE.INDXC(L))THEN
        DO 23 K=1,N
          DUM=A(K,INDXR(L))
          A(K,INDXR(L))=A(K,INDXC(L))
          A(K,INDXC(L))=DUM
23      CONTINUE
      ENDIF
24  CONTINUE
    DO 30 I = 1,N
30      TQ(I) = B(I,1)
    RETURN
    END
```

**Include File fadapt2.inc**

```
      INTEGER AGESZ,YRSZ,RESSZ,PARSZ,NA,NY,NYMOD,NPARA,NAGQMOD,
     1        NAGFMOD, NRESID
      PARAMETER (AGESZ = 10)
      PARAMETER (YRSZ = 12)
      PARAMETER (RESSZ = 50)
      PARAMETER (PARSZ = 10)
      DOUBLE PRECISION NMOD(AGESZ,YRSZ), FMOD(AGESZ,YRSZ),
     1         BIMOD(AGESZ,YRSZ),  SELMOD(15), TERMOD(YRSZ),
     2         ABMOD(AGESZ,YRSZ), RESID(RESSZ)
      DOUBLE PRECISION   CDAT(AGESZ,YRSZ), ABDAT(AGESZ,YRSZ)
     1        WDAT(AGESZ,YRSZ), M, PAR(PARSZ), INITIAL(PARSZ)
      INTEGER AGFMOD(AGESZ), AGQMOD(AGESZ)
      COMMON /MOD/ NMOD,FMOD,BIMOD,SELMOD,TERMOD,AGQMOD,AGFMOD,
```

```
1           ABMOD, M
  COMMON /DAT/ CDAT, ABDAT, WDAT
  COMMON /SIZES/ NA, NY, NYMOD,NPARA,NRESID, NAGFMOD, NAGQMOD
```

## Data Files Called by FADAPT

Abundance at age data (from a survey) **Filename abun.in**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 20.0 | 20.0 | 40.0 | 40.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| 46.2 | 48.2 | 48.4 | 96.8 | 96.3 | 48.2 | 47.9 | 47.9 |
| 44.0 | 47.5 | 50.3 | 50.5 | 99.5 | 99.0 | 48.8 | 48.5 |
| 32.0 | 36.9 | 41.8 | 44.3 | 42.3 | 83.4 | 78.9 | 38.9 |
| 20.0 | 19.0 | 23.7 | 26.9 | 26.3 | 25.2 | 45.8 | 43.3 |
| 7.5 | 11.0 | 11.5 | 14.4 | 14.8 | 14.4 | 12.5 | 22.7 |
| 9.0 | 4.1 | 6.7 | 7.0 | 7.9 | 8.1 | 7.2 | 6.2 |

Catch at age data **Filename cat.in**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 18 | 13 | 27 | 36 | 18 | 22 | 22 | 27 |
| 41 | 32 | 32 | 85 | 85 | 53 | 52 | 62 |
| 91 | 75 | 79 | 104 | 205 | 249 | 123 | 143 |
| 80 | 72 | 81 | 110 | 106 | 251 | 237 | 135 |
| 60 | 45 | 56 | 81 | 79 | 90 | 165 | 179 |
| 23 | 26 | 27 | 43 | 44 | 52 | 45 | 94 |
| 27 | 10 | 16 | 21 | 24 | 29 | 26 | 26 |

Control parameter data **Filename inits.in.** The character fields to do not appear in the original.

| | |
|---|---|
| 7 8 | Number of ages and years in catch data |
| 4 4 | Number of F and number of q parameters |
| 0.2 | Natural mortality |
| 2 3 4 5 | Ages for the F parameters |
| 2 3 4 5 | Ages for the q parameters |
| .09 .3 .48 .6 .1 .2 .2 .1 | Initial parameter estimates |
| .05 .15 .5 .8 1. 1. 1. | Selectivity |
| .4 .3 .3 .4 .4 .5 .5 .6 | Terminal Fs on oldest age |