FISHERY ANALYSES and SIMULATION TOOLS

(FAST 2.0)

a software program and manual developed by

JEFFREY W. SLIPKE and MICHAEL J. MACEINA

Department of Fisheries and Allied Aquacultures

Auburn University, Alabama 36849 USA

2001

Preface

The purpose for the development of this software was to provide fishery biologists and managers a simple Windows-based computer program to simulate and evaluate the dynamics of exploited fish populations. The program provides for the evaluation of proposed length and bag limit regulations on both moderate to heavily exploited fisheries as well as in low or no exploitative recreational fisheries.

To our knowledge, three common computer programs were previously available that specifically examine and evaluate the dynamics of fish populations, and include the Generalized Inland Fishery Simulator (GIFSIM) model (Taylor 1981), RAMAS (Ferson and Akcakaya 1988), and MOCPOP (Beamesderfer 1991). Although there is some overlap in the functions performed by available programs, they nevertheless vary widely in their scope, utility, and ease of use. Most widely available fish modeling programs in use today were written before the advent of the Windows operating system. Although accurate and useful, these DOS based programs can be difficult to load and operate, and often result in the user being booted-out of the program. Many DOS-based programs also are, to some extent, incompatible with the Windows operating system widely used today. Another drawback of these older programs is their lack of interactivity with the user. Editing of individual data points can be difficult if not impossible with some of the programs available today. Also, the ability to cut and paste data is not available in non-Windows based programs, making these programs incompatible with modern spreadsheet and graphics programs.

These DOS-based programs also do not perform non-linear regression analyses. GIFSIM requires length-weight parameters and MOCPOP requires length-weight and von Bertalanffy (1938) growth function parameters as inputs. Hence, both programs depend on the output of other programs such as FISHPARM (Prager et al. 1987) or other statistical packages that compute non-linear terms for input parameters before modeling can be performed.

The Statistical Analysis System (SAS 1988) has been used to conduct fishery simulations (Allen and Miranda 1995, Maceina et al. 1998a), but site licenses for SAS make it cost prohibitive for many government agencies and private individuals and programming is extremely difficult unless the user is well trained in SAS. Similar to the older DOS based programs, large

amounts of data are generated from modeling and graphic presentation is necessary for interpretation. Graphic interfacing between SAS statistical output and SAS GRAPH is tedious and programming skills are necessary.

Since their early development in the 1980's, computer programs to analyze and model fish populations have aided researchers and managers in their efforts to simulate the dynamic nature of exploited fish populations. Programs such as GIFSIM, RAMAS, MOCPOP and the tools offered by statistical programs including SAS remain quite functional and useful tools. However, our profession and society has fully entered the "computer-technology revolution" which started in the mid-1980's with PC's and accelerated starting in mid-1990's with the Windows operating system. The advent of powerful and fast personal computers allows complex mathematical functions to be performed and enormous data sets to be analyzed in a few seconds or less. Advancing computer technology improves our ability to process vast amounts of information. Thus, our goal is to update previous software programs to improve modeling capabilities for fisheries biologists.

The basic principles used to model fish populations and estimate yield and catch were presented in Beverton and Holt (1957) and Ricker (1975). In this era where computational tools were limited and primitive, we believe the pioneer work of these authors and other workers during the last three quarters of this century was of enormous magnitude and scope. The mathematical computations we use in the Fishery Analyses and Simulation Tools (FAST) program are essentially unchanged from those presented by Ricker (1975).

The foundation of fish population dynamics was derived primarily for marine stock assessment, although applications for exploited freshwater fish populations can be found. We have broadened the scope of these previous approaches to include recreational aspects of fisheries where harvest is not a mutually exclusive or primary goal of management. During the past 10 to 15 years, the advent of protective slot length limits, high length limits, and reduced or alternating bag limits for different sizes of fish are widely used management tools in freshwater and even now in some marine fisheries where fish consumption is not a priority. Over the past ten years, we have noticed greater use of modeling applied to the management of freshwater sport fisheries. Our past emphasis has primarily focused on freshwater recreational fisheries and

include both exploitative and catch and release fisheries. In FAST, we have attempted to adapt principles that have been primarily used for large fishery stock assessment and applied these to sport fisheries. However, FAST can be used for any type of fishery.

The background material presented in this manual was adapted from course materials from Mike Maceina's graduate class in fish population dynamics at Auburn University and from other short courses on this subject. We have attempted to cover just the basic information needed for a student or professional to get started in modeling fish populations. In this manual, background information on growth, mortality, recruitment, and modeling are presented. More detailed and in- depth information with additional terms to conduct analyses and other topics related to fish population dynamics can be found in Hillborn and Waters (1992) and Quinn and Deriso (1999).

Jeff Slipke
Mike Maceina

July 2000

TABLE OF CONTENTS

1. INTRODUCTION

Installing FAST

FAST requires about 15 MB of disk space and can be installed on any PC running Windows 95 or higher.

1. Start Windows (if not already started). As a precaution, shut down any applications that might be currently running.

2. If you have a previous version of FAST installed on your system, make sure you uninstall it and delete the FAST folder and all of its contents before proceeding with the new installation.

3. If installing FAST with 3.5 inch diskettes, insert Disk 1 into the Floppy drive, select **Run** from the **Start** menu, and type a:\setup.exe.

    If installing FAST with a CD-Rom disk, just insert the disk into the drive and FAST will automatically load onto your hard drive.

4. Follow the instructions in the Setup program. The default location for installation is the Program Files Folder.

Why model fish populations?

Fisheries management often involves balancing the needs and desires of conflicting user groups within the constraints of the environmental and biological processes that control fish populations. Each action an analyst proposes will, if implemented, impact not only the fish population or community being managed, but also the suite of constituent groups that use the fishery. Accordingly, analysts must rely upon appropriate information and analysis before a management action can be implemented. The first step involved in developing alternative management possibilities is the collection and interpretation of all pertinent data needed to address different goals for a fishery.

Mathematical models to simulate fish populations have been developed to aid fisheries managers and analysts in their attempt to synthesize and interpret the large amount of data needed to develop a sufficient understanding of a fishery that allows for more effective management (Taylor 1981). A model is defined as a simplified representation of a process or a

system (Starfield and Bleloch 1986). Modeling allows the analyst to explore the potential risks and rewards of management options quickly and efficiently (Johnson 1995). Models also allow analysts to evaluate the effects of uncertainty on any potential decisions, to explore trade-offs among multiple objectives, to explore alternative actions and possible outcomes, or to help design or refine data collection efforts (Johnson 1995). Working interactively with clients, constituent groups and the public, modeling allows the analyst to communicate predicted effects of any management decision, which can ultimately be used in the final decision making process.

Minimum-length limits, slot-length limits, and bag limits are perhaps the most widely used and valuable tools used by managers to protect and manipulate fish populations (Wilde 1997). Evaluations of length limits abound in the literature and generally compare pre- and post-limit angler survey and population characteristic data. Modeling offers the analyst the advantage of being able to evaluate a range of potential outcomes that might result from a proposed regulation, before actually recommending the regulation. Finally, in self reproducing populations, recruitment variability can be estimated and even understood, but in many instances cannot be controlled. Predictions for a fishery can encompass this natural stochastic behavior.

For the analyst, one of modeling's greatest assets is being able to deal with uncertainty. In some instances, there may be a wide bound of statistical confidence about some parameter that is a necessary input for modeling. Sometimes data for a certain parameter could not be collected and a "best guess" must be made. Including this uncertainty or variability can provide insights on the limits of predictability (Rice 1999). Rice (1999) further stated "it may be more useful to focus on the magnitude and consequences of uncertainty than on trying to predict effects." In examining complex interactions among populations Rice (1999) stated that "success may depend less on what we know than on how we cope with what we don't know."

Fish populations and fishing regulations

A fish population is defined as a community of interbreeding individuals of the same species in a locality. A fish stock is a self contained population with little or no emigration and immigration. The terms population and stock are often intertwined, but stocks usually refer to larger marine systems and possibly laucristrine systems (e.g., Great Lakes) where stocks or sub-

populations exist in a large geographic area. These fish are not entirely reproductively isolated from other stocks, but can be managed with different regulations because they may express unique population characteristics or fisheries with variable harvest regimes.

Three dynamic rate functions govern fish populations and these include recruitment, growth, and mortality (Figure 1-1). In naturally sustained populations, fish produce sufficient offspring that ultimately grow to sexual maturation. In most cases, fisheries can be established for low or non-reproducing populations by stocking. After hatching in the wild or if juvenile fish are stocked, fish must grow to recruit to an adult size or a size that is desired for capture. The population can be described by many characteristics including density and biomass, and/or by size and age structure. Fish mortality can divided into two sources, fishing and natural. Fishing mortality includes consumptive harvest as well as hooking and tournament mortality, whereas, natural mortality occurs due to old age, diseases, parasites, or predation. Self sustained populations typically remain in a state of dynamic equilibrium as fish die or are removed from a population and new recruits enter the fishery.

Over the past century, fishery biologists have collected tremendous amount of data on these three major functions that regulate populations. This research has proven invaluable to our understanding the nature of fish population dynamics. Because all three of these forces work in combination to regulate populations, modeling assists in processing the complex interactions among these three interactive forces.

Johnson and Martinez (1995) suggested the regulation selection process for fisheries management contain eight steps (Figure 1-2). Simulation modeling directly applies to Step 3 in the process, but can be used to identify potential regulations (Step 2), and in Step 8 to compare predicted model results to empirical data collected on the fisheries. Another type of modeling such as bioenergetics modeling could be used to predict indirect effects (Step 4). For example, increasing the length limit and/or reducing the bag limit for a predatory game fish would be expected to decrease the amount of available forage in a system.

The modeling approach that we use for this software requires age structure data and incorporates a single-species approach. Understanding the complex dynamics of fish populations is greatly enhanced by the ability to age most species. Accurately aging fish and obtaining an

REPRODUCTION
- self reproducing
- stocking

mortality | *growth*
(natural) | *recruitment*

FISHERY
- density and biomass
- size and age strucuture

mortality

NATURAL MORTALITY
- old age
- diseases
- predation

FISHING MORTALITY
- harvest (exploitation)
- hooking (release and death)
- tournament (release and death)
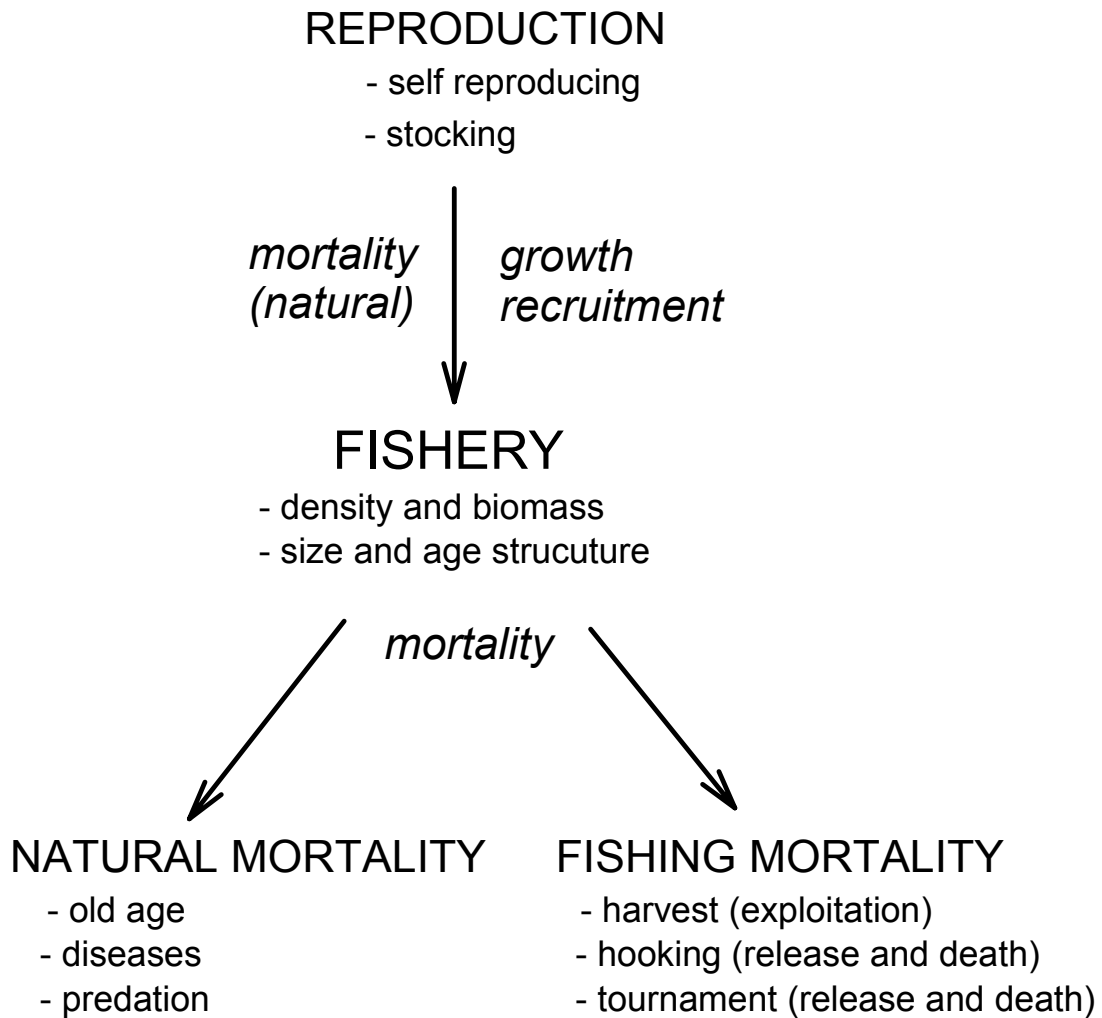
Figure 1-1. Schematic of the components of an exploited fishery. The three major forces or functions that regulate the population include growth, mortality, and recruitment (italics).

1. Establish goals for the fishery

2. Identify potential regulations

8. Monitor and evaluate

THE REGULATION SELECTION PROCESS

3. Predict direct effects

7. Implement the regulation

4. Predict indirect effects

6. Obtain formal public input

5. select candidate regulations
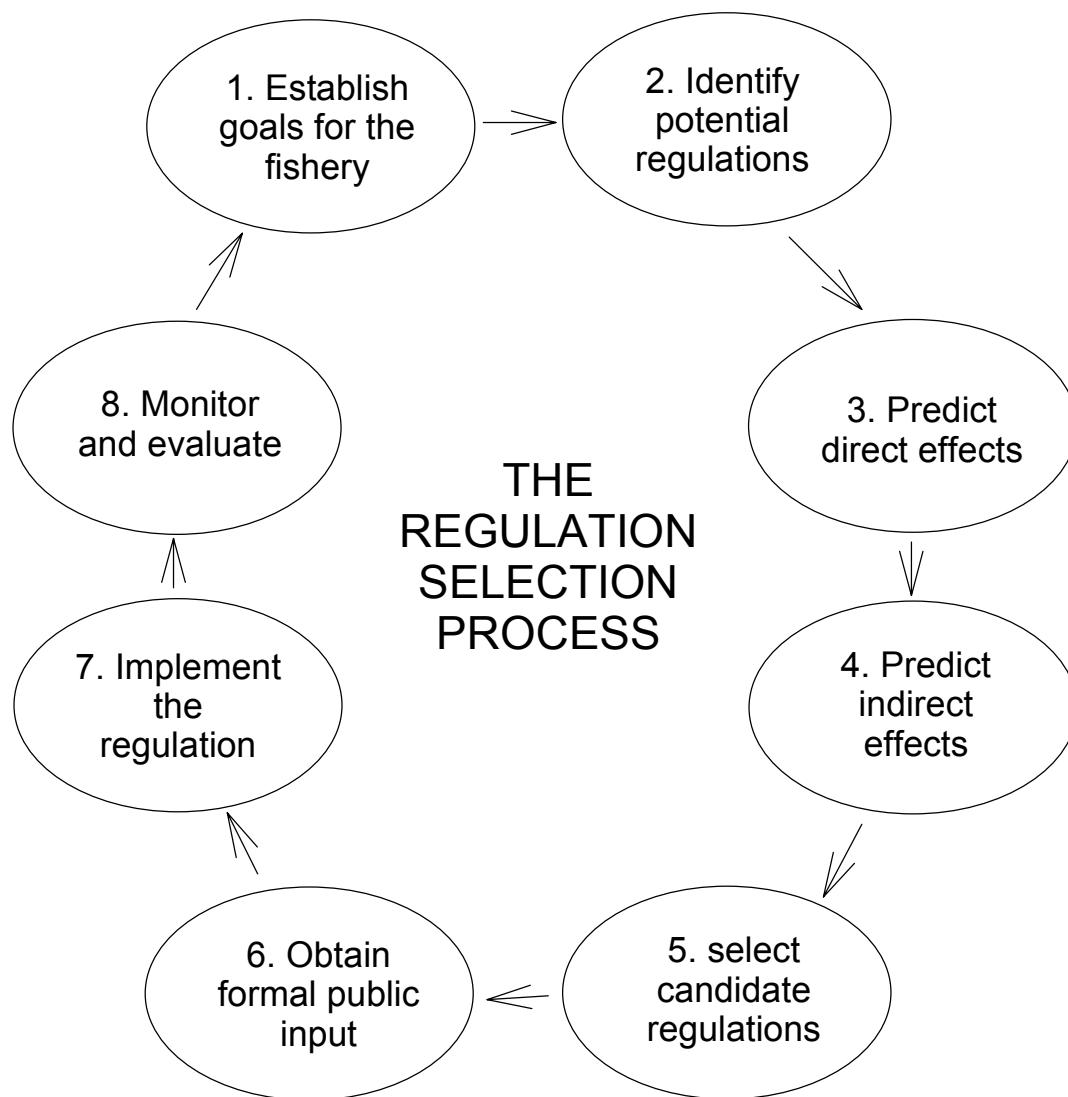
Figure 1-2. The regulation selection process as illustrated by Johnson and Martinez (1995).

adequate sample from the entire population is paramount to producing accurate model predictions.   From age data, growth, mortality, and recruitment can be estimated. In many instances, accurate age data must be obtained from examination of otoliths and fish must be sacrificed. Biologists may be hesitant to remove large numbers of fish and particularly larger specimens from a water body to obtain this information. However, if modeling predictions from a length or bag limit are desired for the entire population including the response of memorable or trophy size fish, this data is necessary. Crawford et al. (1999) examined otoliths from angler caught trophy fish provided to taxidermists to estimate growth and longevity of largemouth bass in Florida and this can partially circumvent the dilemma of sacrificing larger specimens during sampling.

The next chapter presents the FAST tools for computing length-structure (stock density) indices and relative weights for all the freshwater fish listed in Fisheries Techniques (Murphy and Willis 1996) in the chapter authored by Anderson and Neumann (1996). The following three chapters describe growth, mortality, and recruitment functions that are needed to simulate population dynamics and the procedures in FAST to compute these terms will be presented. Next, we bring together the processes of growth, mortality, and recruitment to simulate the responses of fish populations using the Beverton-Holt equilibrium yield model. We provide four chapters that provide real examples that employ the applications of FAST to analyzing fish populations with corresponding management implications. Finally, the last chapter provides a summary of FAST utilities including, spreadsheet and data management, graphics, and other miscellaneous topics. PDF and HTML files that contain publications and papers that we used in our examples for this manual are included to supplement user interpretation and provide background information. These papers are found on the CD-ROM and can be read with the Adobe Acrobat Reader 4.0 software, also included on the FAST CD-ROM. With the exception of the paper from Fisheries Review, these papers and the FAST Users Manual are all searchable using the Find feature of the Acrobat Reader. For best results, use the Acrobat reader 4.0 version, as some of the graphics contained in the FAST Users Manual will not display in earlier versions of the Acrobat Reader.

```
┌─────────────────────────────┐   ┌─────────────────────────────┐   ┌─────────────────────────────┐
│           GROWTH            │   │         RECRUITMENT         │   │          MORTALITY          │
│                             │   │                             │   │                             │
│ Von Bertalanffy Growth      │   │  ┌─────────┐  ┌──────────┐  │   │ Conditional Fishing         │
│ Function:                   │   │  │  Fixed  │  │ Variable │  │   │ Mortality:                  │
└─────────────────────────────┘   │  └─────────┘  └──────────┘  │   │    - cf                     │
```

GROWTH

Von Bertalanffy Growth Function:
  - L_4, K, t_o

Weight:Length Relation:
  - **intercept (a)**
  - **slope (b)**

Maximum Age Observed:
  -**MaxAge**

RECRUITMENT

Fixed   Variable

MORTALITY

Conditional Fishing Mortality:
  - **cf**

Conditional Natural Mortality:
  - **cm**

YIELD-PER-RECRUIT MODEL

Length Limit Options:
  1) Fixed minimum length
  2) Variable minimum length
  3) Slot length limit

Size of Cohort:
  - **Initial number of recruits (No)**

Spawning Potential Ratio:
  - **Yes or No**

Lengths of Interest

DYNAMIC POOL MODEL

Recruitment Options:
  1) Fixed
  2) Random (uniformly distributed)
  3) Random (normally distributed)
  4) Strong year-classes every Nth year
  5) Strong year-classes at random intervals

Species Being Modeled **(Species)**

Minimum Length **(min TL)**

Length of Simulation **(Num Years)**

OUTPUT

Graphical:
  - bivariate plots and 3D contour plots

Raw Data:
  - tabular format of variables

OUTPUT

Graphical:
  - bivariate plots by year or by age

Raw Data:
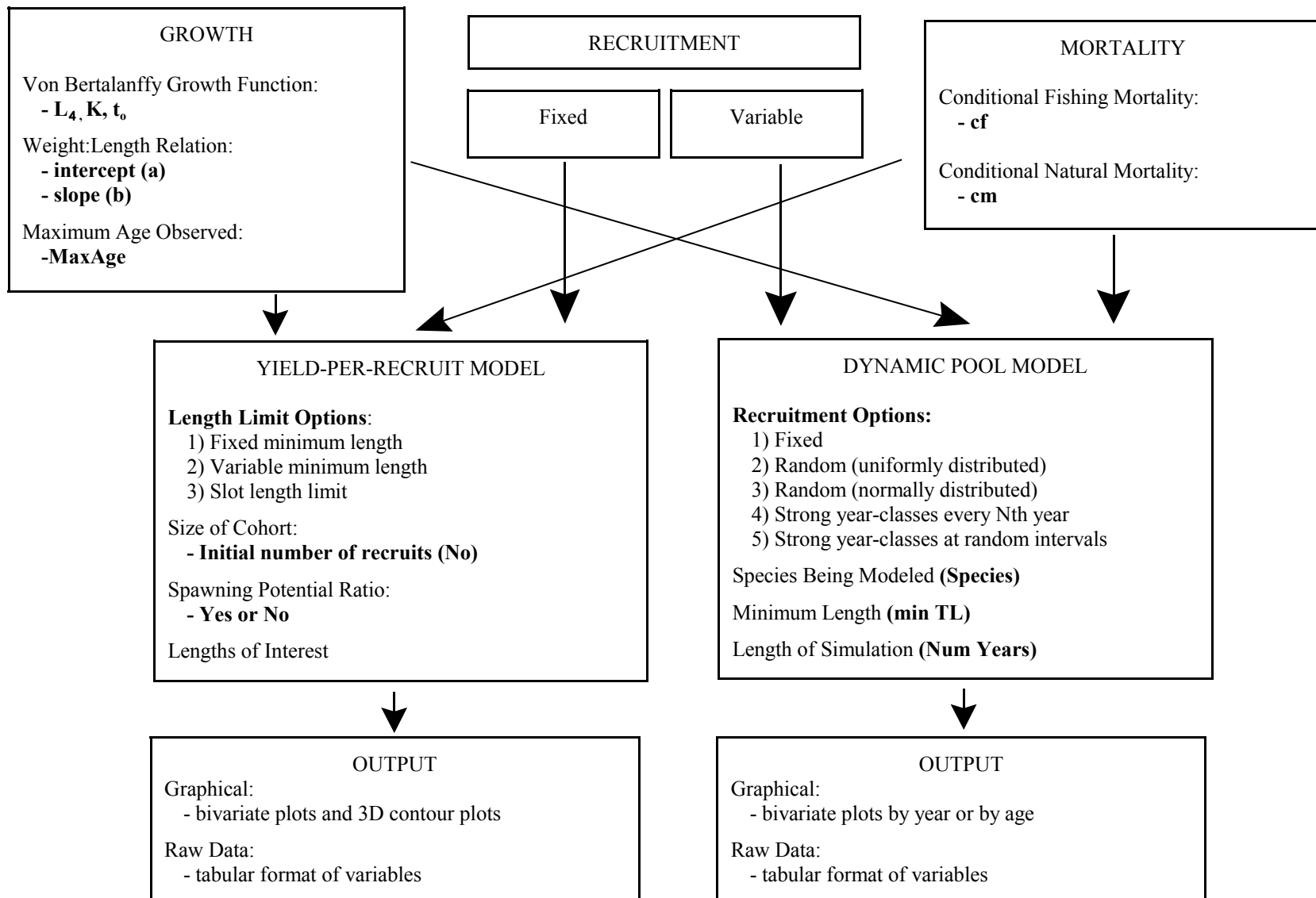 - tabular format of variables

Figure 1-3. Simplified schematic flow chart of the FAST modeling program. Required input parameters are identified by bold print.

2. COMPUTATION OF STOCK DENSITY
AND RELATIVE WEIGHT INDICES

<u>Background</u>

FAST provides the user with stock density indices and mean relative weights (W_r) for different length categories. Length categories and standard weight equations to compute W_r for 36 freshwater species listed in Anderson and Neumann (1996) is provided in FAST. Using a dynamic pool model, FAST can predict stock density indices under constant or variable rates of natural and fishing mortality and these values can be compared to empirical values observed from a population. Such comparisons can be useful to the analyst to verify and calibrate models, or to make predictions on the effects of length and bag regulations on stock density indices. Relative weights are provided as supplemental information to the analyst; our simulation modeling procedures do not predict W_r's.

Proportional stock density (PSD) and relative stock density are quantitative descriptors of length-frequency data (Anderson and Neumann 1996).   PSD is defined as:

$$PSD = \frac{\text{Number of fish \$ minimum quality length}}{\text{Number of fish \$ minimum stock length}} \text{ X } 100 \qquad\qquad 2:1$$

where minimum length categories have been defined by Anderson and Neumann (1996) and are provided in FAST. PSD is expressed as a whole number and not as a percentage with values ranging from 0 to 100.

Relative stock density is defined as:

$$RSD = \frac{\text{Number of fish \$ specific length}}{\text{Number of fish \$ minimum stock length}} \text{ X } 100 \qquad\qquad 2:2$$

where minimum and specific length categories have been defined by Anderson and Neumann

(1996) and are provided in FAST. This index will include preferred size and larger fish (RSD-P), memorable size and larger fish (RSD-M), and trophy size fish (RSD-T). These traditional RSD values have the same properties as PSD.

In addition to these indices, FAST will compute incremental RSD values. Incremental RSD values are calculated as the percentage of stock-length fish consisting of individuals between the minimum lengths for the size categories (Anderson and Neumann 1996). Thus, RSD S-Q is the percentage of fish from the total sample of fish stock size and larger than are between stock and quality length. The RSD Q-P ratio is the number of fish that are between quality and preferred size divided by the total number of stock size and larger fish. Similarly, RSD P-M, and RSD M-T include the ratio of preferred to memorable size fish and memorable to trophy fish divided by the total number of stock size and larger fish. FAST can compute both incremental and traditional stock density indices.

Relative weight is an index of the weight:length relation in fish and is defined as:

$$W_r = \frac{W}{W_s} \text{ X } 100 \qquad\qquad 2{:}3$$

where:

W = observed weight (g); and

W_s = the length-specific standard weight (g) predicted by a weight:length regression
constructed for the species (Anderson and Neumann 1996).

The general form of the standard weight equation is:

$$W_s = a + b(\log_{10}L) \qquad\qquad 2{:}4$$

where:

a and b are the intercept and slope values for the $\log_{10}$(weight):$\log_{10}$(length) standard
weight equation; and

L = total length in mm.

A W_r value of 100 represents a weight:length relation at the upper 75th percentile from all populations of a species sampled to derive the W_s equation. Typically, W_r values less than 80-85 represent a "skinny" or emaciated fish and for a population would suggest inadequate food resources and likely slow growth. Conversely, for W_r values of 100 and higher, fish are in good condition, plumb, adequate food resources exist, and growth is probably good. FAST computes individual W_r's for each fish, then computes a mean value for each incremental length category. Complete explanations for computing and interpretation of stock density and W_r indices can be found in Anderson and Neumann (1996).

<u>Using FAST to compute stock density indices and mean W_r</u>

From the toolbar on the upper left corner of the main window, choose **Population Parameters** under the **Run/Analyze** menu. An embedded spreadsheet will appear (for an explanation of the spreadsheet module used in FAST, see Chapter 11 of this manual). Data must be properly entered into the first sheet of the spreadsheet. The first row must contain column headers as text, with the associated numerical data entered in the rows beneath the header row. By default, the headers for this option are Age (years), Length (mm), and Weight (g). Accordingly, age data must be entered into column 1, length data in column 2, and weight data in column 3. Missing data should be entered as a period (.). If the analyst wishes to save the age, length and weight data, it should be done before proceeding.
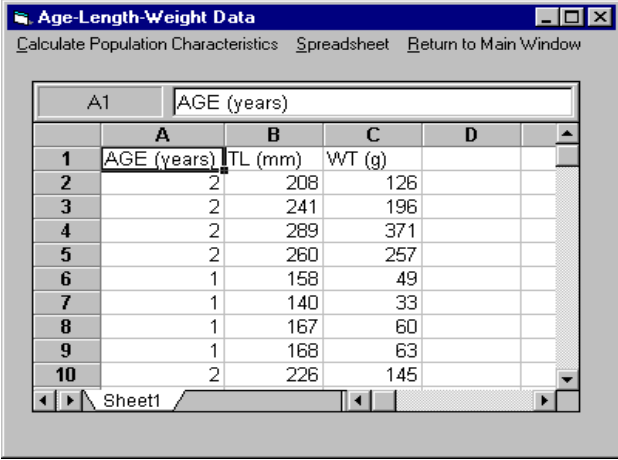
Once all data is entered into the spreadsheet, the next step is to choose **Calculate Population Characteristics** from the menu. This action will display a **Choose Species** window, allowing the analyst to choose a species from the list provided or to choose **Other** if your species is not listed. Choosing a species will populate the text boxes with appropriate length categories, the standard weight equation, and the recommended minimum length (TL) for the standard weight equation for each species. The values for each species in the list were taken from Anderson and Neumann (1996). All boxes must contain values in order for the analysis to proceed, therefore, if other is chosen or a species contains incomplete data, then the analyst must enter numbers in the appropriate boxes. Once a species is chosen and all text boxes contain

values, click OK to proceed. An new sheet containing the output will be added to the spreadsheet module. Traditional stock density indices (PSD, RSD-P, RSD-M, and RSD-T), and incremental stock densities (RSD S-Q, RSD Q-P, RSD P-M, and RSD M-T) are given. Finally, at the bottom of the Output, the mean relative weights are given for substock, stock, quality, preferred, memorable, and trophy length groups.

Performing the population parameters analysis also populates spreadsheets used by the other FAST analysis tools. The spreadsheet for the catch-curve analysis is populated with number-at-age data, the weight-length regression tool is populated with length and weight data, and the von Bertalanffy solver is populated with mean length-at-age data.

Example: Computation of stock density and W_r indices for a smallmouth bass population

From the toolbar in the upper left corner click on **Run/Analyze** and then select **Population Parameters**. Next, click on **Spreadsheet** and select **Activate Worksheet**. In the active spreadsheet, click on **File** and select **Read**. In the next step, you will be opening a sample file (**Pickwick_SMB.vts**) that contains age, length, and weight data for a smallmouth bass *Micropterus dolomieui* population collected in fall 1995 and spring 1996 with electrofishing from Pickwick Reservoir in Alabama (Slipke et al. 1998). One year was added to ages of fish collected in fall 1995 as Slipke et al. (1998) assumed growth was nil between fall 1995 and spring 1996. A copy of this paper can be found as a PDF file included with this software on the CD-Rom disk. Open the **Pickwick_SMB.vts** file from the Sample Files folder, which by default is located in the **C:\Program Files\FAST** directory. Close the **VCI Formula One Workbook Designer** window to return the spreadsheet to its embedded form. Data will automatically be pasted into the **Age-Length-Weight Data** spreadsheet.

Click on **Calculate Population Characteristics**. The window containing **Choose Species** will appear.

Choose smallmouth bass and the length categories for stock, quality, preferred, memorable, and trophy will appear along with the coefficients for the standard weight equation. Click on **OK**, and the spreadsheet is returned, and the stock density indices and mean relative weights for each incremental length group are computed and displayed in an output sheet.

Age-Length-Weight Data

Calculate Population Characteristics   Spreadsheet   Return to Main Window

A1   Age

	A	B	C	D	E	F
1	Age	Mean TL	Number			
2	1	179.38	189			
3	2	261.37	268			
4	3	338.36	121			
5	4	413.86	43			
6	5	453.6	5			
7	6	510.7	10			
8	7	490	1			
9	8	478.25	4			
10	11	528	1			
11						
12	Traditional Stock Density Indices					
13	PSD	RSD-P	RSD-M	RSD-T		
14	41.17	19.13	6.19	1.64		
15						
16	95% Confidence Intervals					
17	PSD	RSD-P	RSD-M	RSD-T		
18	37.05 - 45.28	15.84 - 22.42	4.18 - 8.21	.58 - 2.7		
19						
20	Incrementalal Stock Density Indices					
21	RSD S-Q	RSD Q-P	RSD P-M	RSD M-T		
22	58.83	22.04	12.93	4.55		
23						
24	Mean Relative Weights					
25	Sub-stock	Stock	Quality	Preferred	Memorable	Trophy
26	93.74	95.07	95.76	101.9	107.06	104.54

Output / Input

From the criteria of Anderson and Neumann (1996), this smallmouth bass population is well balanced, contains a high proportion of larger fish, and mean relative weights values are relatively high. To print the output, **Activate Spreadsheet**, and under **File**, click on **Print** and follow the instructions for your printer. **Page Setup** and **Print Preview** options are provided to modify the print output.

3. GROWTH

Background

   Growth is defined as the change in body size over time and can be expressed in units of length or weight. After hatching, fish must grow to survive the larval and juvenile phase and ultimately reach a desired size in the fishery or become mature. Fishery biologists have long recognized the importance of growth for managing fisheries. Holding other factors equal, populations that express faster growth are amenable to management with higher length limits, whereas if growth is slow and the population is stunted, then high harvest rates with a low or no length limit may be an option. Knowing this, fishery biologists have attempted to manipulate growth of predator species by stocking forage fish that can be readily preyed upon (Noble 1981). Although sometimes controversial, fishery biologists stock non-native stocks, subspecies, and species in an attempt to increase growth and size of fish caught by anglers. Habitat manipulation can also increase growth. For example, in smaller water bodies, primary production can be enhanced via nutrient additions which increases food resources at lower trophic levels.

Computation of the von Bertalanffy growth function

   To describe growth for modeling, typically annular age data is necessary. Fish age is usually determine by the examination of hard parts including otoliths, scales, vertebrate, cleithrium bones, and spines. Growth can also be estimated by using known age fish or by mark-recapture tagging data for fish of different sizes. To assess growth, a representative sample of fish should be collected from a population, length and weight recorded (weight is used to compute a weight:length relation), and a hard structure removed for later aging. From this data, mean lengths-at-age or mean back-calculated lengths from annuli can be used to describe fish growth over time using the von Bertalanffy (1938) growth equation. This equation is used by FAST for computing growth and associated length-at-age computations where length (L) at some age or time (t) is described as:

$$L_t = L_4(1 - e^{-k(t - to)})$$
3:1

where:

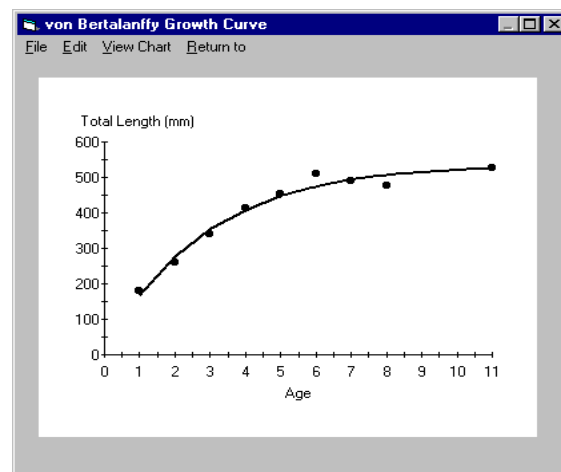> L_4 = maximum theoretical length (length infinity) that can be obtained;
>
> k = growth coefficient;
>
> t = time or age in years;
>
> t_o = is the time in years when length would theoretically be equal to zero and;
>
> **e** = exponent for natural logarithms

Fish growth described by the von Bertalanffy equation is illustrated below.

If sufficient and accurate data are collected, nearly all fish populations display this growth form. Growth in length is typically fastest early in life, then decreases over time as fish reach maximum age and length. The growth coefficient (k) will always be a negative number and its response on the graph between age 0 or t_o and L_4 is analogous to a slope. As the absolute value of k increases holding L_4 and t_o constant, then growth is faster. Most fish are about 5 to 10 mm long when hatched; therefore, the regression line should theoretically intercept the y-axis (length) at 5 to 10 mm when time or age equals zero. However, FAST and other statistical packages such as SAS and FISHPARM derive k, L_4, and t_o simultaneously through numerous interactions. The result is an equation with parameters that minimize the residuals, or error between the regression line and the observed values similar to any least-squares procedure. Thus, the extrapolated regression

line can intercept the x-axis either to the right or to the left of age 0. Thus, t_o is a correction factor to improve the fit between length and age.

To compute L_t for a given set of von Bertalanffy growth parameters where:

$L_4 = 600$ mm;

$k = 0.25$;

$t_o = -0.5$;

and substituting these terms into equation 3:1 for a two year old fish ($t = 2$) then:

$L_t = 600(1 - e^{-0.25(2 - -0.5)})$ then;

$L_t = 600(1 - e^{-0.625})$ then;

$L_t = 600(1 - 0.535) = 279$ mm.

Thus, the von Bertalanffy equation with these parameters predicts that the average length of two year old fish in the population will be 279 mm.

The von Bertalanffy equation can be inverted to predict the time it takes a fish to reach a certain length. This is an important computation that is used in the models to predict the time of recruitment (t_r) to a certain minimum or slot length limit. To compute t_r, we need to solve for t in equation 3:1. For example, to compute the time for a fish to reach a proposed length limit of 356 mm using our von Bertalanffy terms described earlier would be as follows:

$356 = 600(1 - e^{-0.25(t - -0.5)})$, divide the left side by 600 and multiply exponent;

$356/600 = 1 - e^{-0.25t - 0.125}$, subtract 1 from each side;

$0.593 - 1 = - e^{-0.25t - 0.125}$, by cancellation, remove the minus from either side;

$0.407 = e^{-0.25t - 012.5}$, take the natural log of either side;

$- 0.899 = -0.25t -0.125$, add 0.125 to either side and then divide;

$(-0.899 + 0.125)/-0.25 = 3.10$ years.

Thus, the time to reach 356 mm was 3.10 years, which is equal to t_r.

Computation of the weight:length function

　　To predict the yield in weight and the mean weight of harvested fish using FAST, the relation

between weight and length must be computed and entered into the software. Weight increases

exponentially as length increases in fish and this non-linear relation is described as:

　　　　$W = aL^b$　　　　　　　　　　　　　　　　　　　　　　　　　3:2

where

　　　　W = weight, usually in grams;

　　　　L = length , usually in mm and typically is expressed as total length (TL).

In the majority of populations, b ranges from about 2.7 to 3.5. For most commercial and sport

fish b is greater than 3.0. The typical weight:length relation is illustrated in below.
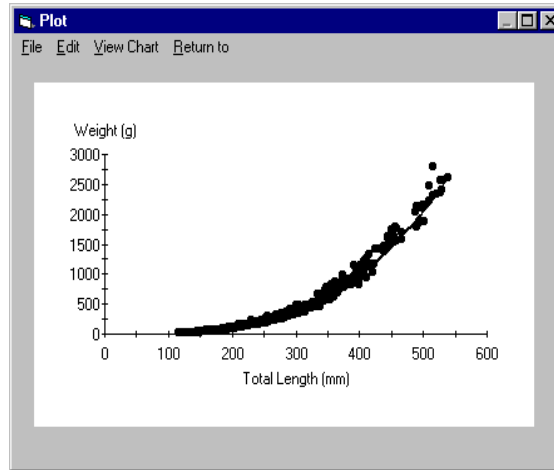
To simplify the computation of the weight:length relation, common log or $\log_{10}$ transformation of

the raw weight and length data is performed. This linearizes the relation to:

　　　　$\log_{10}(W) = a + b* \log_{10}(L)$　　　　　　　　　　　　　　3:3

The intercept value (a) is the linearized form of a from the non-linear equation 3:2, but these

values are not equivalent. The slope (b) from equation 3:3 is identical to the power function in the non-linear equation 3:2.   FAST uses coefficients computed from the double $\log_{10}$ transformed linear regression equation (3:3).

Below is the computation for the weight:length regression for a sample of five fish.

Total length (mm)	Weight (g)	$\log_{10}$(Total length)	$\log_{10}$(Weight)
100	10	2.00	1.00
200	113	2.30	2.05
300	408	2.48	2.61
400	1,071	2.60	3.03
500	2,343	2.70	3.37

$\log_{10}$(Weight) is regressed against $\log_{10}$(Total length) and the linear regression is computed:

$$\log_{10}(W) = -5.728 + 3.370*\log_{10}(L)$$

To convert this linear equation to the non-linear equation 3:2 compute $10^{-5.728}$ which equals 0.000001871. Thus, for the above data, the weight:length relation can also be expressed as:
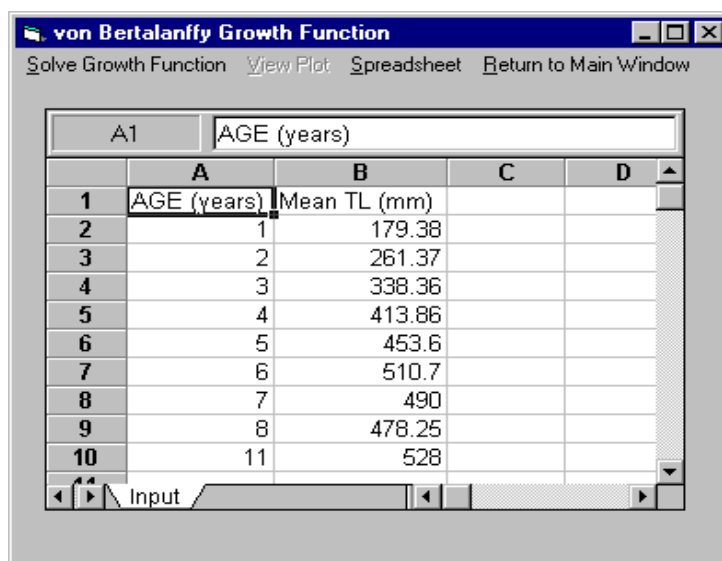
$$W = 0.000001871(L^{3.370})$$

Many of the older modeling programs use the non-linear form for describing the weight:length relation.

Using FAST to compute the von Bertalanffy growth and the weight:length functions

From the menubar on the main window of either the **Yield-Per-Recruit Model** or the **Dynamic Pool Model**, click on **Run/Analyze** and select **von Bertalanffy Growth Function**. An embedded spreadsheet will appear (for an explanation of the spreadsheet module used in FAST, see Chapter 11 of this manual). Data must be properly entered into the first sheet of the spreadsheet. The first row must contain column headers as text, with the associated numerical data entered in the rows beneath the header row. By default, the Input sheet is shown and in column A, enter the age in years and in column B, enter the mean length which is defined in the

heading as total length (TL in mm). A minimum of four mean lengths-at-age data points are needed because three coefficients (L_4, k, and t_o) must be computed and at least 1 degree of freedom for error is needed. The lengths for length-structure indices are provided for a number of species and are programed in millimeters. Therefore, we recommend that other length units be converted to millimeters. A sample file that contains mean length-at-age data has been provided, or the data can be entered manually. For the sample file, activate the spreadsheet and open the **vonBert.vts** file from the Sample Files folder, which by default is located in the **C:\Program Files\FAST** directory. Close the active spreadsheet to return the spreadsheet to its embedded form.

	von Bertalanffy Growth Function			
Solve Growth Function	View Plot	Spreadsheet	Return to Main Window	

	A1	AGE (years)		
	A	**B**	**C**	**D**
1	AGE (years)	Mean TL (mm)		
2	1	179.38		
3	2	261.37		
4	3	338.36		
5	4	413.86		
6	5	453.6		
7	6	510.7		
8	7	490		
9	8	478.25		
10	11	528		

Input

Once the mean length-at-age data have been entered, click **Solve Growth Function** and two choices are given; 1) **Solve for Linf, K, and to** and 2) **Hold Linf constant, Solve for K and to**. The first choice will compute a least-squares fit to the data through iteration. The analyst may wish to use or examine the second choice if specimens from the sample of fish did not approach L_4 or bias existed in the sample for younger and smaller fish.

To compute the weight:length regression, all data can be entered on a spread sheet by clicking on **Run/Analyze** then clicking on **Weight-Length Regression**. Length and weight are entered in columns A and B, respectively. Data can be entered directly into the spreadsheet cell-by-cell or pasted in from another spreadsheet application. A sample file (**WL_Regress.vts**) is provided

in the sample files folder. Each row of data must contain a length-weight pair, as missing values will not be accepted. After data are entered, click **Run W-L Regression** in the upper tool bar and the results of the regression will be displayed on the output sheet. FAST automatically places the coefficients of the von Bertalanffy and weight:length functions in the model parameters section of the main modeling window where these terms are delineated.   If the analyst wants to use another program to compute the coefficients for the von Bertalanffy growth and weight:length functions, these can be manually entered.

In addition, the von Bertalanffy growth and weight:length functions can be computed for raw age, length, and weight data by choosing the **Population Parameters** under the **Run/Analyze** menu. Age in years, length, and weight are entered in columns A, B, and C respectively. The analyst can enter data on this spreadsheet or data can be imported from another spreadsheet as mentioned earlier. **Calculate Population Characteristics** is the option for this window and if a species is selected from the list provided, FAST will compute mean relative weight for each incremental size group and associated size-structure indices (see Chapter 2). After this, return to the main window and choose **von Bertalanffy Growth Function** and **Weight-Length Regression** under the **Run/Analyze** menu to calculate the terms of the von Bertalanffy growth function for mean lengths-at-age and the weight:length regression coefficients.

Interpretation of the FAST output for the von Bertalanffy and weight:length functions

For the von Bertalanffy growth function, the results will show if convergence criteria were met, if an optimal solution was found, and how many iterations that solver had to run to find the coefficients that displayed minimum sums of squares error or residuals. If a message is given that convergence criteria were not met, then the regressions coefficients are not valid and under any circumstances should not be used or interpreted.

```
von Bertalanffy Growth Function                                    _ □ ✕
Solve Growth Function   View Plot   Spreadsheet   Return to Main Window

        A1              von Bertalanffy Solver Results

        A          B          C         D         E         F
 1   von Bertalanffy Solver Results
 2
 3   Convergence Criteria Met with 6 Iterations: Optimal Solution Found
 4
 5   R-squared 0.9749973            Prob > F    0.0001
 6
 7   Parameter Estimate
 8   Linf       538.566
 9   K          0.348
10   to        -0.074
11
      Results  Residuals  Input
```

For the von Bertalanffy growth function to compute an equation, by definition, length increments must decrease at some point later in life. In some instances, inaccurate data or low sample sizes particularly for older fish will cause the solver to not compute a growth equation. Therefore, more data or data substituted from other sources for older fish must be entered.

A coefficient of determination or r-squared value is given and computed by dividing the model sum of squares by the total sum of squares. A probability value for F is given to reject the null hypothesis that there is no relation between age and length. However, hypothesis testing to determine if this regression is statistically significant is awkward because L_4, k, and t_o are not independent variables and these coefficients are simultaneously determined. The values of the three coefficients are given in the output. If the analyst decides to hold L_4 constant, then choose **Hold Linf constant, Slove for K and to**, enter a **Fixed Length Infinity** value in the window and click **OK**. For this example, enter 575 which in mm equates to about the largest smallmouth bass caught by anglers in this system. The same output is provided in the **Results** and note that **Linf** is 575, and **K** and **to** are slightly different compare to the results when **Linf** is not held constant.

To view a graphical representation of the output, click **View Plot** and a plot of age versus length is displayed with the regression line and observed lengths-at-age. In this window, click on **View Chart** and select **Residual Plot**. The residual for a data point is the observed length-at-age

subtracted from the predicted length-at-age and shows the analyst if there is any bias in the pattern of the predicted values. Ideally, the analyst would want accurate predictions from the growth function for the range of lengths-at-age that may be modeled to explore the effects of various length limits. For example, if the analyst was interested in modeling the effects of a 203, 229, or 254 minimum lengths, the predicted values from the von Bertalanffy growth function should be similar to the observed values. By clicking **Growth Curve** the plot of lengths-at-age and the regression line are returned.
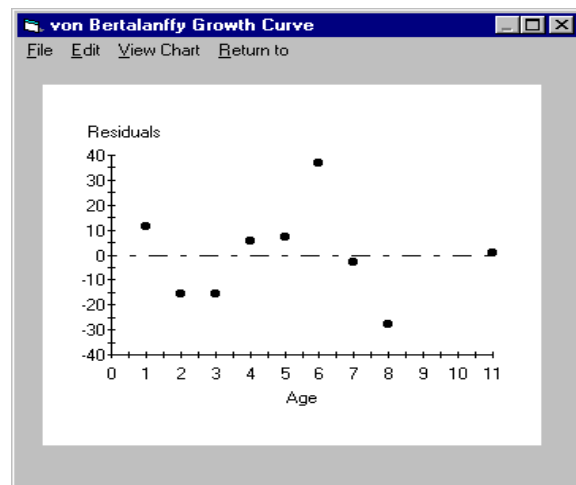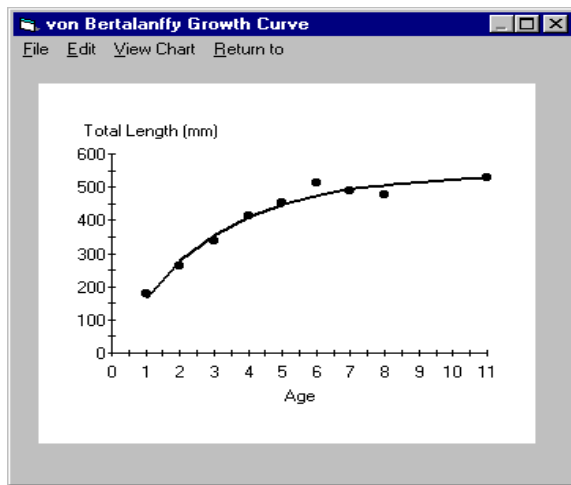
For the weight:length regression output, a typical spreadsheet provided by most statistical packages is given. The model, error, and total degrees of freedom, and the sums of squares and mean squares are given. An F-value is computed by dividing the model mean squares by error mean squares and a probability of rejecting the null hypothesis is given. The null hypothesis for this regression is that the slope of the $\log_{10}$(Weight):$\log_{10}$(Length) regression is equal to zero, or there is no relation between weight and length. Most of the time, the relation between weight and length is highly significant (P < 0.001) and r-squared values typically exceed 0.95. The r-squared value is given as are the corresponding intercept and slope values.

Weight-Length Regression

Run W-L Regression   View Plot   Spreadsheet   Return to Main Window

| | A1 | | Weight-Length Regression Results | | | |

	A	B	C	D	E	F
1	Weight-Length Regression Results					
2	Analysis Of Variance Table					
3						
4			Sums of	Mean		
5	Source	DF	Squares	Square	F-value	Prob > F
6	Model	1	120.47148	120.47148	87221.457	0.0001
7	Error	640	0.8839768	0.0013812		
8	Total	641	121.35545			
9						
10	R-squared					
11	0.9927158					
12						
13	Variable	Estimate				
14	Intercept	-5.536447				
15	Slope	3.2788688				

ANOVA Table ⟍ Residuals ⟍ Input

The weight:length relation can be plotted by clicking on **View Plot** and a plot of the non-linear regression line and the data points are provided. In this window, click on **View Chart** and the choices of displaying the **Log-Log W-L Regression**, the **Residual Plot** for the log-log W-L regression, or back to the **W-L Regression** are provided. The **Residual Plot** is useful for detecting outliers or influential data points. Outliers in weight:length regressions occur due to natural variation, but may be due to incorrect data entry. This tool allows the analyst to detect outliers, assess the validity of a data point, and make any corrections if needed.

3-10
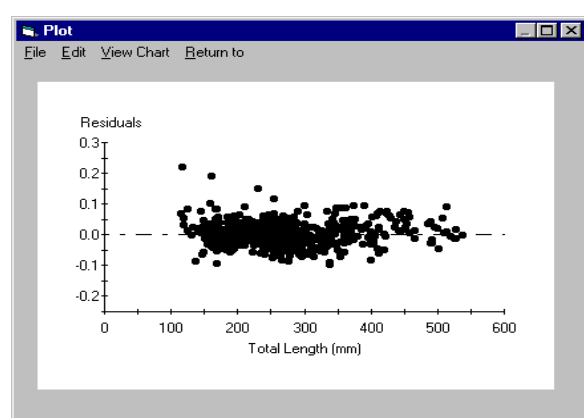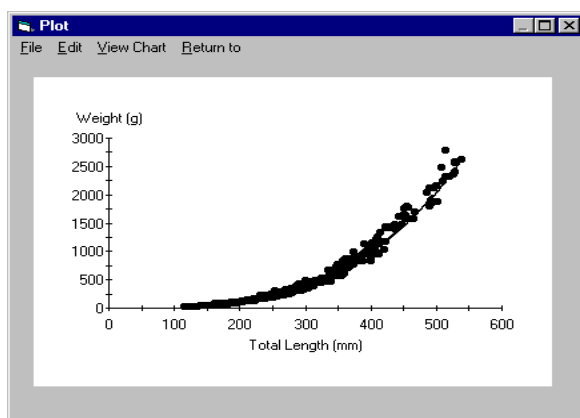
4. MORTALITY

Background

    All fish die. Death or mortality rates can be partitioned into two components, fishing and natural mortality. Fishing mortality is the result of harvest and removal of fish, but hooking mortality and tournament induced mortality can also be considered in this category. Natural mortality is attributed to old age, diseases, parasites, predation, and to abiotic factors such as weather. Estimates of total annual mortality can be computed from age structure data. However, specific data collection is needed to accurately separate natural and fishing mortality. Similar to growth, the ability to age fish and determine the relative abundances of successive cohorts or year classes facilitates the computation of mortality.

Computation of total mortality rates

    The number of fish in a particular cohort or year class declines at a rate proportional to the number alive at any point in time. This phenomenon can be expressed as change in number of fish over time:

$$d\mathrm{N}/d\mathrm{t} = -Z\mathrm{N} \tag{4:1}$$

where:

    N = number of fish

    t = time

    Z = rate of change in N

Equation 4:1 can be rearranged and integrated to:

$$N_t = N_o e^{-zt} \tag{4:2}$$
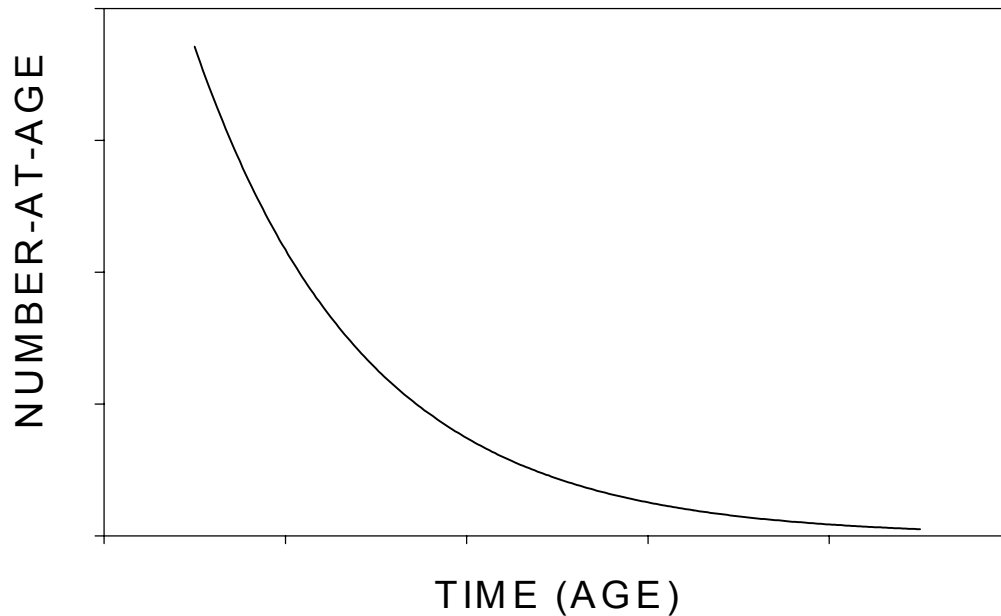
where:

    N_t = number in a year class at time t;

    N_o = original number in a year class;

    Z = instantaneous rate of change.

The exponential decline of a year class of fish is shown by the curve below.

If recruitment was constant each year and mortality among year classes was similar, then this curve would represent a steady decline in the relative abundances of successive year or age classes over time.

The annual survival rate (S) in a population can be defined as:

$$S = N_t/N_o \qquad\qquad\qquad 4{:}3$$

For example, if 100 age-1 fish were captured with some sampling effort and one year later 60 fish of the same cohort were collected with the same amount of effort and no bias in catch rates occurred, survival would be 60% (60/100). The instantaneous annual rate of total mortality can be derived by computing the natural logarithm (ln) of survival:

$$Z = \ln(S) \qquad\qquad\qquad 4:4$$

For a survival rate of 60%:

$$Z = \ln(0.60) = -0.511;$$

and from Equation 4:2, if $N_t = N_o e^{-zt}$ then:

$$N_t = 100e^{-0.511(1)} = 60;$$

which is equivalent to computing N_t from the survival rate. Thus, why use instantaneous rates? This will be apparent when computations are presented that separate fishing and natural mortality when both types of mortalities occur at the same time in a fishery.

For example, take the natural log of each side of $N_t = N_o e^{-Zt}$, then

$$\ln(N_t) = \ln(N_o) - Z(t) \qquad\qquad 4:5$$

which is computationally analogous to simple liner regression; $\ln(y) = a - b(x)$.

Equation 4:5 is know as a catch-curve regression or catch-curve analysis. To compute a catch-curve regression, a representative sample of all ages of fish are collected from a population, and the natural log of abundance or number-at-age (y variable) is regressed against age (x variable).

Table 4.1

Age	Number	ln(Number)
1	1000	6.908
2	500	6.215
3	250	5.521
4	125	4.828

It is obvious from the changes in number that annual survival is 50.0% The regression of ln(Number) against age is:

$$\ln(\text{Number}) = 7.6015 - 0.6934(\text{Age})$$

The slope (-0.6934) is the instantaneous rate of total annual mortality (Z). Survival (S) is also defined as:

$$S = e^{-Z} \qquad\qquad\qquad 4{:}6$$

and for the computations for the last example:

$$S = e^{-0.6934} = 0.50$$

or survival equals 50%.

   Catch-curves are normally fitted to a set of number-at-age data when full recruitment to the fishery has occurred. If no fish from a particular age group are collected, but fish are collected from older age classes, then a value of zero is paired for that missing age group or year class. When this occurs, one must be added to all number-at-age data because the natural log of zero cannot be computed. The natural log of one is computed as zero when no fish are collected from a particular age group. However, a value of one is added to all year classes or ages that have been collected if and when a missing year class occurs. Thus, slight bias occurs when a value of one is added to number-at-age data when computing catch-curve regressions. The assumptions of catch-curve regression to estimate overall natural mortality include:

1) Reproduction or recruitment is constant.

2) Survival is equal among year classes.

3) Survival is constant from year to year.

4) Natural mortality and fishing mortality are the same each year and among all year classes.

5) Catch-curves are fitted to samples that are representative of the true age structure of the population.

Rarely are all of the assumptions of catch-curve analysis met, but computation can give an approximate estimate of overall mortality. Deviations, or the residuals about a catch-curve line, usually represent variation in recruits to the population as shown below, thereby violating the first assumption. This error, or the analysis of residuals in catch-curve regressions, can provide insights into recruitment variability and potential environmental variables related to fluctuations in reproductive success (Maceina 1997; see Chapter 5).

$Z = -0.536$
$S = 58.5\%$
$r^2 = 0.77$
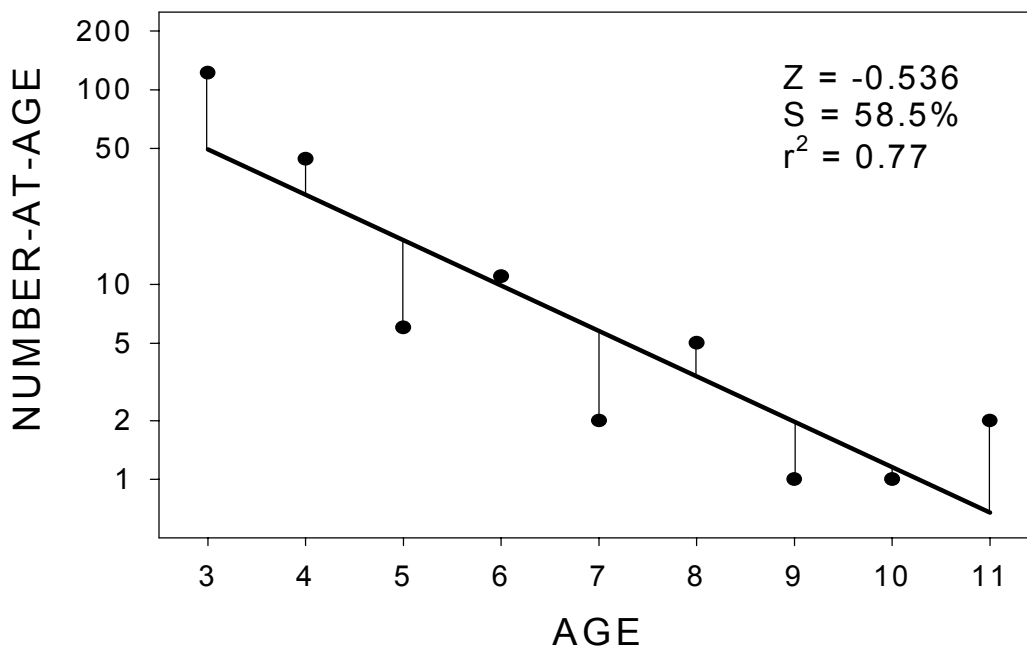
Older and rarer fish collected from a representative sample can influence the slope of the catch curve. For example, catch-curve regressions were computed for the following data in Table 4.2.

Table 4.2

Age	Number
3	61
4	37
5	9
6	15
7	3
8	2
9	0
10	0
11	0
12	1

From the data in Table 4.2, regressing ln(Number) against age yields a slope or Z of -0.464, and confers an annual survival rate of 63% (Figure 4-1). The regression was highly significant (P < 0.01) and the coefficient of determination was 0.84. This regression can be run in FAST by choosing **Catch-Curve Analysis** under the **Run/Analyze** menu of the main window, or can be computed from any statistical program. However, the analyst may wonder about including data from a single 12 year old fish and the data for age 9, 10, and 11 year old fish when no fish of these ages were collected. A catch-curve regression could be conducted again with elimination of age 9 to 12 year old fish. Because all ages of fish were represented for fish age 3 to 8, a value of one was not added to number-at-age. The slope value for this regression (P < 0.01; $r^2 = 0.91$) is -0.689 which confers an annual survival rate of 50% (Figure 4-1). It is obvious from a plot of the data that the single age-12 fish is a highly influential data point in the analysis (Figure 4-1). In addition, the residual value (1.18) for this observation was greater than for any other data point (range of other residuals -0.91 to 0.44).

To provide for less bias, an alternative type of catch-curve regression can be computed using a weighted regression technique. Detailed descriptions of this procedure are provided in Steel and Torrie (1980), Montgomery and Peck (1982), and Fruend and Littell (1991).
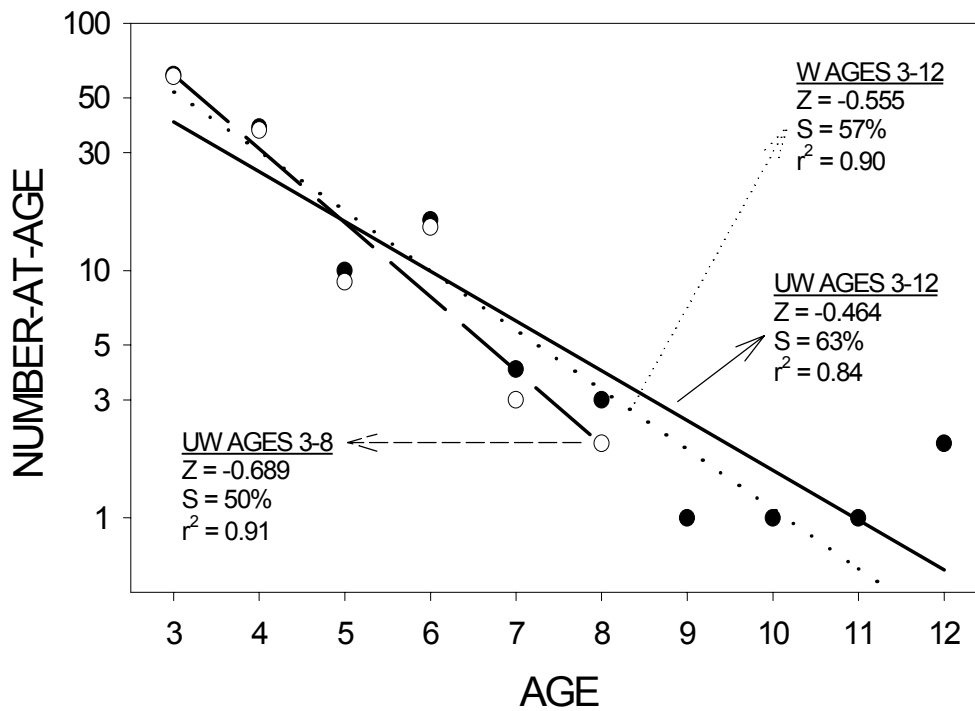
Figure 4-1. Unweighted (UW) catch-curve regression for age 3 to 8 fish (open circles, dashed lines), unweighted catch-curve regression for age 3 to 12 fish (solid lines and circles), and weighted (W) catch-curve regression for age 3 to 12 fish (dotted line, data points not shown).

Weighted regression deflates the importance of rare and older fish when computing the slope of a catch-curve regression. When unweighted least-square regressions are computed, heterogeneous variances can occur, whereas weighted regression can be used to create more homogenous variances. For catch-curve regressions, higher residual values at older ages would be indicative of heterogenous variances.

For simple linear regression, the intercept (b_o) and slope (b_1) can be described and solved from:

$$\text{Solve}(b_o, b_1) = \sum_{i=1}^{n} (y_i - b_o - b_i x_i)^2$$

For weighted regression, this expression becomes

$$\text{Solve}(b_o, b_1) = \sum_{i=1}^{n} w_i (y_i - b_o - b_i x_i)^2$$

where the weights (w_i) are:

$$w_i = \text{predicted } \log_e(\text{number-at-age}) + 1.$$

A value of one is added to the weighting term because predicted number-at-age values less than one will be negative. Negative weights in weighted regression causes the individual observations to be deleted from the analysis which is incorrect. Essentially, weighting number-at-age proportions out the contribution of each product and cross-product for each observation to compute a least-squares fit to the data. Weights for each observation are computed from unweighted regression, then these weights are used in the weighted regression. For the number-at-age data from Table 4.2, computations for weights used in the weighted catch-curve regression appear in Table 4.3.

Table 4.3

Age	Number	ln(Number +1)	ln(Number)	Predicted Weights
3	61	4.127	3.688	4.688
4	37	3.638	3.224	4.224
5	9	2.303	2.761	3.761
6	15	2.773	2.297	3.397
7	3	1.386	1.834	2.834
8	2	1.099	1.370	2.370
9	0	0.000	0.906	1.906
10	0	0.000	0.443	1.443
11	0	0.000	-0.021	0.979
12	1	0.693	-0.484	0.516

Using the weights in Table 4.3, the weighted catch-curve regression for this example yields a slope of -0.555 (S = 57%) which is intermediate to the unweighted catch-curve regression for fish 3 to 12 years old and the unweighted catch-curve regression for 3 to 8 year old fish (Figure 4-1). The coefficient of determination between the number-at-age data for weighted regression is 0.905, higher than 0.836 for the unweighted regression for age 3 to 12 year old fish.

Another method for computing Z uses the terms of the von Bertalanffy equation and the length-frequency data of fish sampled from a population. This formula was presented by Gulland (1976) and is:

$$Z = K(L_4 ! l_x)/(l_x ! l_r) \qquad\qquad 4:7$$

where:

K = von Bertalanffy growth coefficient and is always a negative;

L_4 = length infinity for the von Bertalanffy growth equation;

l_x = mean length of fish sampled in the population above either the length limit or the minimum length of fish harvested by anglers; and

l_r = minimum length of recruitment to the current legal fishery or minimum length of fish harvested by anglers.

FAST does not provide a utility for computing Z using this formula, but derivation of Z can easily be computed using a hand calculator after l_x has been computed. Maceina et al. (1998a; see HTML file for paper) used this formula to estimate over-all survival rates of crappie in Weiss Lake, Alabama. Terms of the von Bertalanffy equation for this population can be found in the FAST sample file entitled **Weiss_crappie.par**. The mean length of crappie greater than the 254 mm minimum length was 288 mm from a sample collected in 1996. With an L_4 and K coefficients of 330.97 and -0.716, Z equals -0.905 (= -0.716(330.97 - 288)/(288 - 254) which confers a survival rate of 40%.

Computation of fishing and natural mortality rates

   After computing the instantaneous total mortality rate (Z) in a exploited fishery, this rate needs to be divided into fishing mortality (F) and natural mortality (M). F is defined as the instantaneous rate of fishing mortality when natural mortality is occurring concurrently. M is defined as the instantaneous rate of natural mortality when fishing mortality is occurring concurrently. Thus;

$$Z = F + M \qquad\qquad\qquad\qquad 4:8$$

Equation 4:2 can be rearranged to include both fishing and natural mortality:
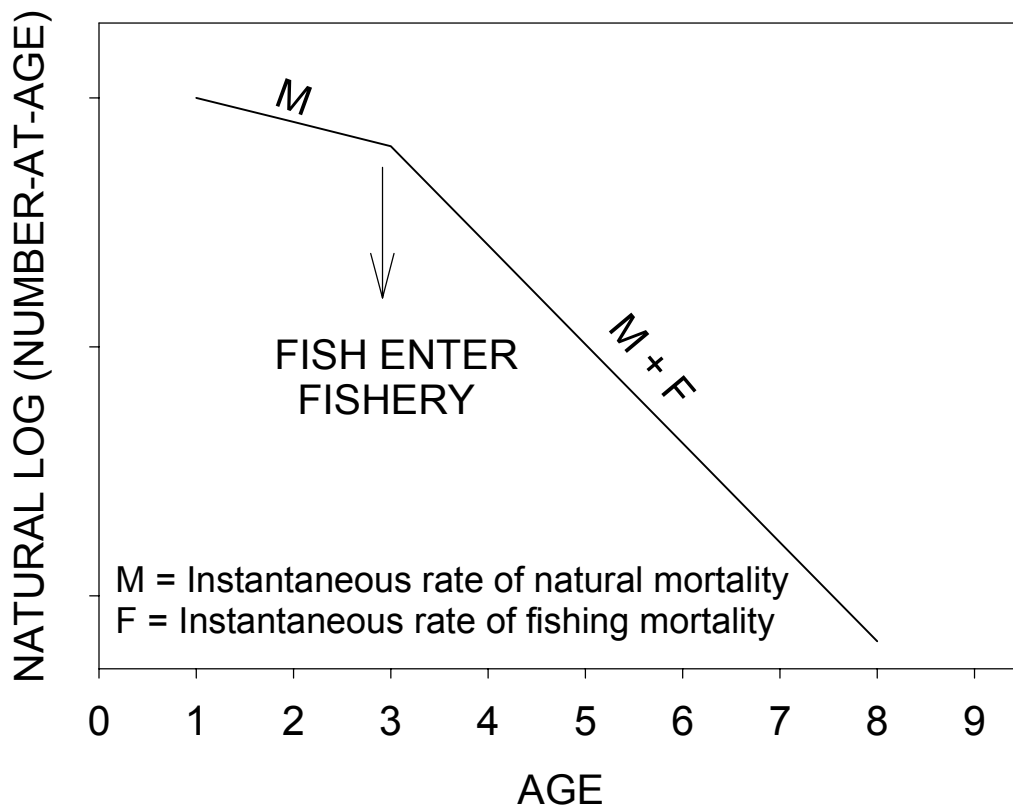
$$N_t = N_o e^{-(F + M)t} \qquad\qquad\qquad\qquad 4:9$$

or

$$N_t = N_o e^{-(F)\, t} e^{-(M)\, t} \qquad\qquad\qquad\qquad 4:10$$

   The relation between number-at-age and age for a moderately to heavily exploited fishery typically displays a break or bend in the relation when plotted as shown below. For example, if natural mortality was constant between ages 1 to 9 and harvest of fish was initiated at age 3 when

a minimum length was attained, the slope of the line between number-at-age and age would be much greater from age 3 to 9 than between age 1 and 3 where only natural mortality was occurring.

To determine F and M, an exploitation rate needs to be computed. Typically, this is determined from tagging studies, but can be estimated by a wide variety of methods (Ricker 1975; Hillborn and Waters 1992; Quinn and Deriso 1999). Fisheries biologists sample a

<figure>
Y-axis: NATURAL LOG (NUMBER-AT-AGE)
X-axis: AGE, values 0 1 2 3 4 5 6 7 8 9

M

FISH ENTER
FISHERY

M + F

M = Instantaneous rate of natural mortality
F = Instantaneous rate of fishing mortality
</figure>

population of fish, obtain individual lengths, and insert a tag into each fish that can be returned for a reward by anglers. It is important that anglers know a tagging study is occurring in a particular water body, the tag is readily visible, anglers are willing to participate, and if not,

corrections made for angler non-reporting. A tag that has a number specific to a particular fish can also provide information on growth, movement, and size selectivity by anglers. Exploitation rate (u as defined by Ricker 1975) can be computed as:

$$u = \text{Number of harvested fish tagged/Number tagged} \qquad 4\text{:}11$$

For example, if a biologist tags 837 fish and 192 are captured and harvested by anglers, the exploitation rate for that time period is 192/837 = 23%. Tag loss can occur particularly over a period of time, reducing the number of tagged fish available to anglers, and thereby causing exploitation to be underestimated. If a tag loss rate is known, it can be incorporated into equation 4:11. For example, if tag loss was known to be 20% then 192/(837*0.80) would yield an exploitation rate of 29%. Biologists can double tag a sample of fish during an exploitation study to correct for tag loss. For example, if 100 of the 837 fish were double tagged and 25 of these double tagged fish were returned, and only 20 had both tags, then tag loss would be 20% (25-20/25 = 0.20).

Non-reporting of harvested fish is problematic and enigmatic to the biologist (Larson et al. 1991; Maceina et al. 1998b), but needs to be considered when estimating exploitation. Assuming 35% of the anglers who harvest fish do not return the tag, and the 20% tag loss also occurs for this example, then $u = (192)/(0.65)/(837*0.80)$ which confers an exploitation rate of 44%. If non-reporting was 50%, then the estimate of exploitation would increase to 57%.

The expectation of natural death (v as defined by Ricker 1975) is the percentage of fish dying from other causes not related to fishing activity. Annual mortality (AM) incorporates the fish dying naturally while exploitation is occurring. Thus, annual mortality is:

$$AM = u + v \qquad 4\text{:}12$$

Thus, annual survival is also:

$$S = 1 - AM \qquad 4\text{:}13$$

Once exploitation or the natural death rate is estimated, F and M can be computed from:

$$F = u * Z / (1 - S)$$ 4:14

and

$$M = v * Z / (1 - S)$$ 4:15

Conditional fishing mortality (*cf*) is analogous to exploitation(*u*) and would be the exploitation rate when no natural mortality occurs. However, natural mortality will occur in every population over a period of time. Conditional natural mortality (*cm*) is similar to (*v*), except that it is the death rate due to natural causes when no fishing mortality occurs. Where no fishing induced mortality occurs, then *cm* would equal *v*. To estimate natural mortality, data from an unexploited or lightly exploitation population in a particular region would be useful.

If instantaneous rates of fishing mortality (F) and natural (M) mortality are known, then *cf* and *cm* can be computed from:

$$cf = 1 - e^{-F}$$ 4:16

and

$$cm = 1 - e^{-M}$$ 4:17

The following example brings these mortality parameters together. During an investigation, a sample of fish was collected, ages determined, and a catch-curve regression fitted to data from fish that had entered the fishery. The slope or Z value for catch-curve regression was -1.204. Thus, overall survival was 30% (see equation 4:6). During this same time, exploitation was estimated at 40% from a tagging study and this value was corrected for tag loss and angler non-reporting. From equation 4:14, F can be estimated:

$$F = (0.400)*(1.204)/ (1 - 0.300) = 0.688$$

Equation 4:8 can be rearranged so that $M = Z - F$ then:

$$M = 1.204 - 0.688 = 0.516.$$

F, M, and Z are always negative values so absolute values can be used to make these computations. The only exception to this would be if no fishing mortality, natural mortality, or overall mortality occurred, then these values would be zero.

Conditional fishing mortality and conditional natural mortality rates are computed from equations 4:16 and 4:17:

$$cf = 1 - e^{-0.688} = 0.50 \text{ or } 50\%$$

and

$$cm = 1 - e^{-0.516} = 0.40 \text{ or } 40\%$$

Thus, 50% of the fish would die if no natural mortality was occurring and 40% would die if no fishing mortality was occurring. The sum of conditional fishing and natural mortality rates are 90%. However, from the catch-curve regression, annual morality was 70% and survival was 30%. In this example, 70% does not equal 90%. If exploitation (u) was 40% while natural mortality (cm) was occurring, then the expectation of natural death (v) would be 30% which confers an annual mortality rate of 70%.

Conditional fishing mortality, conditional natural mortality rates, and associated instantaneous rates of mortality (F, M, and Z) are used to model fish populations for the following reasons. Typically, both fishing and natural mortality occur at the same time (Type II fishery defined by Ricker 1975). Equation 4:9 ($N_t = N_o e^{-(F + M)t}$) necessitates the use of instantaneous rates (F and M) which are ultimately used to solve for the true rates of exploitation and death due to natural

causes, holding for the effects of each term. In an exploited population, some exploited fish removed from the population would have died from natural causes before being harvested. If little or no exploitation takes place, the relative percentage being removed from the population due to natural mortality would be high. If fishing mortality *(u)* is extremely high, then the percentage of fish dying due to natural causes (*v*) would be low. Thus, as conditional natural mortality increases at fixed levels of conditional fishing mortality, exploitation will be reduced. Conversely, as conditional natural mortality declines for given rates of conditional fishing mortality, exploitation will increase.

In Table 4-4 below, various rates of total mortality and fishing mortality are computed at conditional natural mortalities of 25 and 50%. Notice that at higher levels of conditional fishing mortality, exploitation (*u)* is lower at the higher level of conditional natural mortality. Also note that F values for a given level of conditional fishing mortality are the same at either level of conditional natural mortality.

Table 4-4.

  cm = conditional natural mortality rate
  v = expectation of natural death
  M = instantaneous rate of natural mortality
  cf = conditional fishing mortality rate
  u = exploitation
  F = instantaneous rate of fishing mortality
  Z = instantaneous rate of total mortality
  AM = annual mortality

cm	*v*	*M*	*cf*	*u*	*F*	*Z*	*AM*
0.250	0.250	0.288	0.000	0.000	0.000	0.288	0.250
0.250	0.238	0.288	0.100	0.087	0.105	0.393	0.325
0.250	0.225	0.288	0.200	0.175	0.223	0.511	0.400
0.250	0.212	0.288	0.300	0.263	0.357	0.644	0.475
0.250	0.198	0.288	0.400	0.352	0.511	0.799	0.550
0.250	0.183	0.288	0.500	0.442	0.693	0.981	0.625
0.250	0.167	0.288	0.600	0.533	0.916	1.204	0.700
0.500	0.500	0.693	0.000	0.000	0.000	0.693	0.500
0.500	0.477	0.693	0.100	0.073	0.105	0.799	0.550
0.500	0.454	0.693	0.200	0.146	0.223	0.916	0.600
0.500	0.429	0.693	0.300	0.221	0.357	1.050	0.650
0.500	0.403	0.693	0.400	0.297	0.511	1.204	0.700
0.500	0.375	0.693	0.500	0.375	0.693	1.386	0.750
0.500	0.345	0.693	0.600	0.455	0.916	1.609	0.800

Equation 4:9 is an integral that is ultimately incorporated into the yield-per-recruit and dynamic pool models used in FAST. The GIFSIM (Talyor 1981) and SAS models used by Allen and Miranda (1995) and Maceina et al. (1998a) use this approach to model populations. MOCPOP (Beamesderfer 1991) first removes individuals from the population due to exploitation, then the remaining deaths are assigned to natural causes. Thus, exploitation and

4-16

natural mortality are not computed simultaneously. Uncertainty exists in estimates of *cf* and *cm* and we recommend a wide range of values be considered when attempting to predict the impact of regulation changes on a fish population.

Using FAST to compute annual mortality rates

To model with FAST, rates for **conditional natural mortality** and **conditional fishing mortality** must be provided.   FAST's catch-curve analysis can be used to estimate annual mortality rates for a range of ages.   Additional field studies as described earlier or other data can provide estimates of conditional fishing mortality and conditional natural mortality. In some instances, conditional natural mortality rates for a particular species can be approximated, overall mortality estimated, and the difference then assigned to conditional fishing mortality.

From the menubar on the main window of either the **Yield-Per-Recruit Model** or the **Dynamic Pool Model**, click on **Run/Analyze** and select **Catch Curve Analysis**. An embedded spreadsheet will appear (for an explanation of the spreadsheet module used in FAST, see Chapter 11 of this manual). Data must be properly entered into the first sheet of the spreadsheet. The first row must contain column headers as text, with the associated numerical data entered in the rows beneath the header row. By default, the Input sheet is shown and in column A, enter the age in years and in column B, enter the number-at-age. For this procedure, the analyst should have already computed number-at-age. If no fish were collected for a particular age and data for older fish are present, the analyst must ensure that zeros are entered for the number at the appropriate ages.

To save the data in a .vts file, click on **Activate Worksheet**, and save the file as you would in any other spreadsheet application. Close the **Activate Worksheet** window, the data will reappear, then click on **Run**. Two choices, **Un-weighted Regression** and **Weighted Regression** are provided. By clicking on one of these, the regression is computed and results given.

If number-at-age data has not been computed, then FAST can do this from data entered into the **Population Parameter** spreadsheet (see Chapter 2). Go back to the main window, click on **Run/Analyze**, and select **Population Parameter**. For individual fish, age is entered in column A, length (TL in mm) in column B, and weight (g) in column C. Weights are obviously not
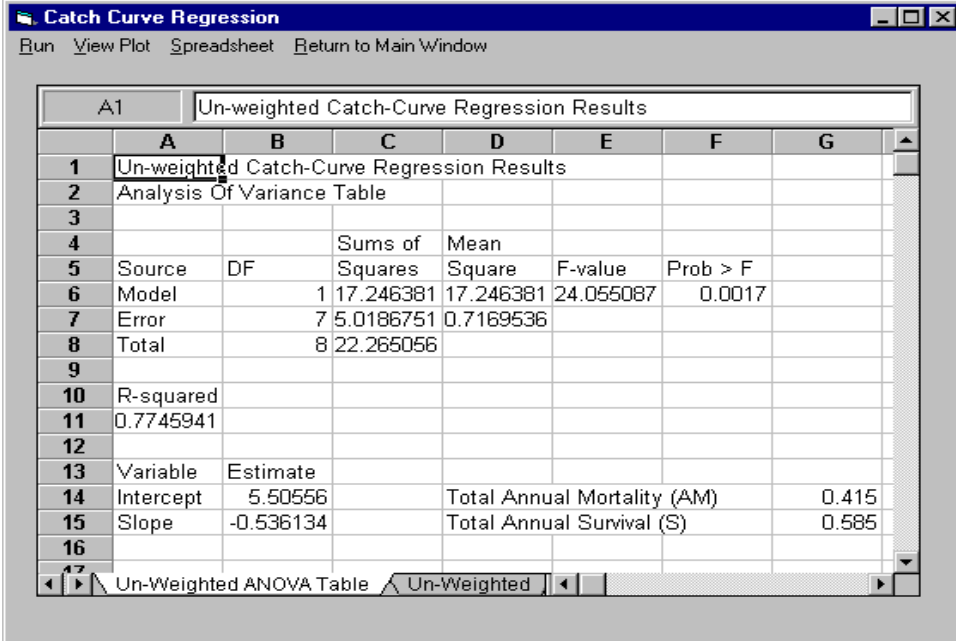
needed to compute number-at-age, and if data is missing just enter a period (.). The **Population Parameter** function also computes a weight:length regression. Conversely, data can be imported from another spreadsheet program, such as Excel, as long as age, length, and weight data would correspond to columns A, B, and C in the FAST **Population Parameter** spreadsheet. The first row in the spreadsheet is reserved for character variables that correspond to the column headers of age, length, and weight.

A sample file (**SMB_CC.vts**) is provided in the sample files folder that contains number-at-age data from a sample of smallmouth bass from Pickwick Reservoir, Alabama, collected with electrofishing in spring 1996 (Slipke et al. 1998). To compute a catch-curve regression for these data, activate the catch-curve spreadsheet and open this file. Close the active spreadsheet to return it to its embedded form then click on **Run**. Two choices, **Un-weighted Regression** and **Weighted Regression** are provided. By clicking on one of these, the regression is computed and results given.

Interpretation of the FAST output for catch-curve regression

The output regression ANOVA table after running either the **Un-weighted Regression** or **Weighted Regression** is very similar to most outputs for other statistical packages. Model, error, and total degrees of freedom, sums of squares, mean squares, an F-value and a probability associated with the F-value are given. The statistical probability value for this example (0.0017) indicates the regression equation is significant and the null hypothesis that the slope of the line between ln(Number) and age is equal to zero can be rejected. The r-square value, and the intercept and slope of the regression are given. The slope is the instantaneous rate of natural mortality (Z) and is -0.536, the survival rate is 58.5% or annual mortality rate is 41.5%, and these are provided.
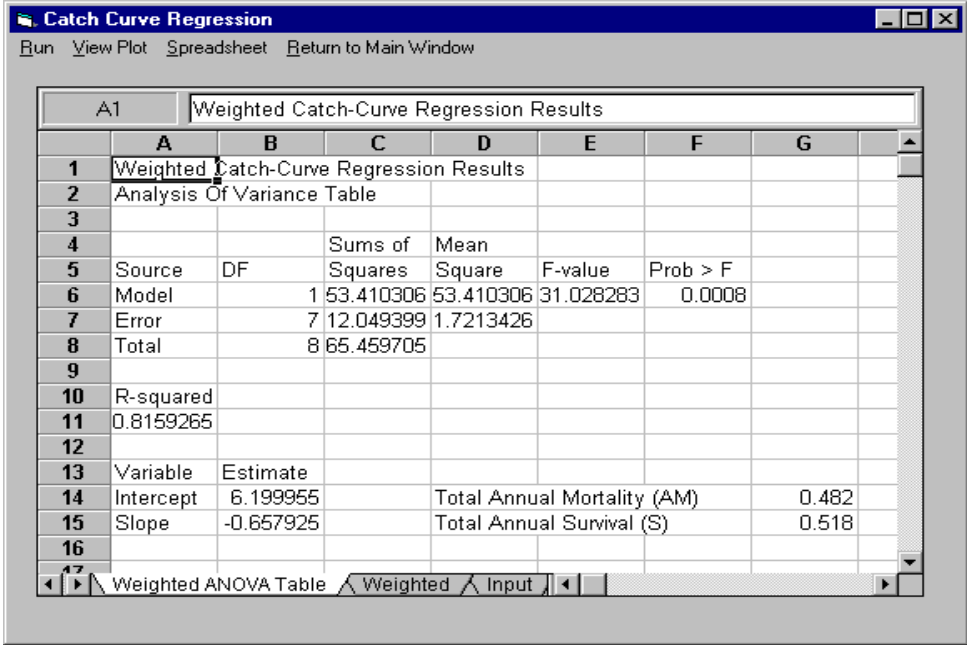

By clicking on the **Un-Weighted** tab in the lower part of the spreadsheet which is between **Input** (raw data) and **Un-Weighted Results**, a spreadsheet like that below is provided that contains the age, number, ln(Number), the predicted number from the catch-curve regression, the predicted ln(Number), and the residual between the observed $\log_e$(Number) and predicted $\log_e$(Number).

4-19

To graphically view the results of the catch-curve analysis, click **View Plot**. A plot of number (or catch-per-age) against age is displayed. From the Plot window, click on **View Chart** to visualize the residual plot for the regression.
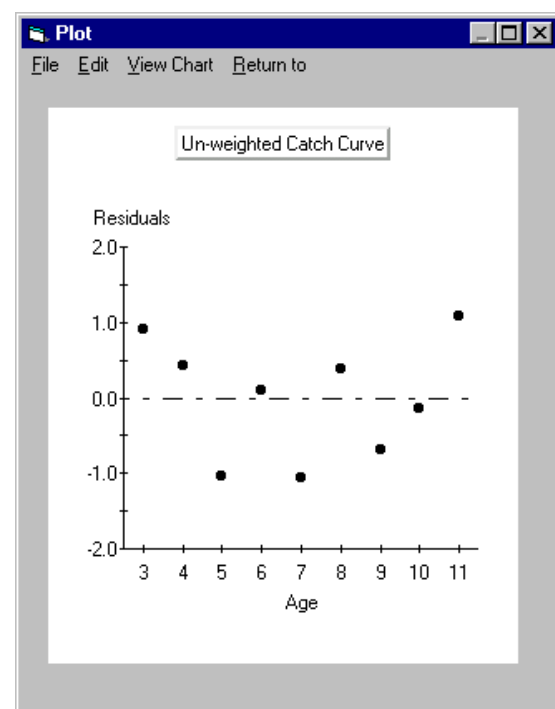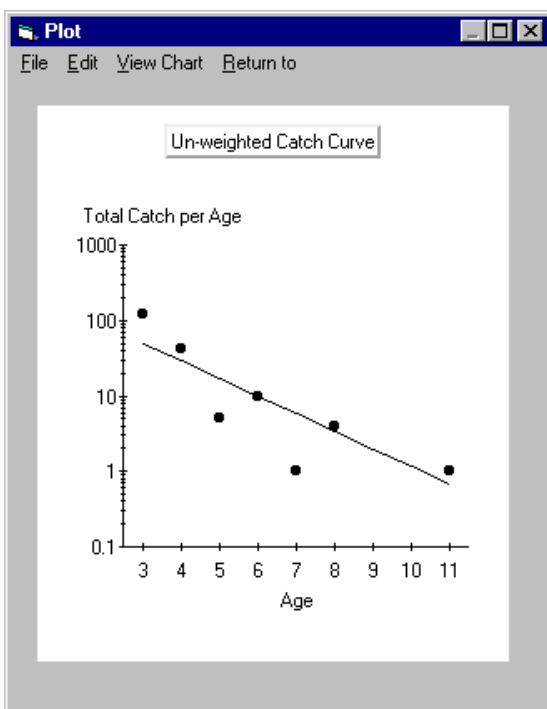
A similar output is produced if weighted regression is used. For this example, the slope value is greater (Z = -0.658) for weighted than for un-weighted regression and this valued conferred an annual survival rate of 51.8%. If few older fish are in the population, weighted regression will compute a steeper slope value, hence a lower survival rate compared to unweighted regression.

Catch Curve Regression
Run   View Plot   Spreadsheet   Return to Main Window

A1 | Weighted Catch-Curve Regression Results

	A	B	C	D	E	F	G
1	Weighted Catch-Curve Regression Results						
2	Analysis Of Variance Table						
3							
4			Sums of	Mean			
5	Source	DF	Squares	Square	F-value	Prob > F	
6	Model		1	53.410306	53.410306	31.028283	0.0008
7	Error		7	12.049399	1.7213426		
8	Total		8	65.459705			
9							
10	R-squared						
11	0.8159265						
12							
13	Variable	Estimate					
14	Intercept	6.199955		Total Annual Mortality (AM)			0.482
15	Slope	-0.657925		Total Annual Survival (S)			0.518
16							

◄ ► Weighted ANOVA Table / Weighted / Input / ◄

Using FAST to estimate natural mortality rates

Partitioning total mortality into rates of fishing and natural mortality requires additional data collection by the analyst. Exploitation estimates are subject to error primarily due to angler non-reporting of fish harvested and tag loss over time. Deriving corrections for these two sources of bias would improve accuracy of an exploitation rate, but these are also difficult to obtain. After estimates of exploitation and total annual mortality are determined, the remaining mortality can be assigned to natural causes and ranges of conditional fishing and conditional natural mortality can be entered into FAST. Alternatively, an analyst can collect age-structure data from an unfished population if available, and conduct catch-curve analysis to determine natural mortality in this unfished population. However, the opportunity to sample an unfished population may be rare or non-existent.

In FAST, we provide the analyst with six computational methods to estimate instantaneous natural mortality (M) and the corresponding conditional natural mortality rate (cm). These methods were obtained from the literature and were derived either from theoretical mathematical relations or from empirical data collected from primarily marine stocks. As we explored these methods, some of these natural mortality rates seemed realistic for many of the fish species that we have worked with. We caution users that these methods may only provide approximations for natural mortality rates. Because these theoretical relations and regression equations were developed for primarily marine species, the assumptions used to fit these equations may not apply to your species. In addition, fit varied among regression equations and predicted values differed among them. If the analyst uses these equations to predict natural mortality, these values should serve as initial estimates that should be bounded by appropriate ranges of conditional natural mortality.

In the remainder of this section, we list six methods to estimate natural mortality, provide a brief background on each of these methods, and provide a table (Table 4-5) with predicted cm values for some of the fish species included in the **Sample files** of FAST. The analyst is encourage to obtain the referenced papers for further information.

1) <u>Quinn and Deriso</u> - Natural mortality is inversely related to longevity among fish populations (Hoenig 1983; Shepherd and Breen 1992). Assuming some proportion of a population older than age-0 that reach a maximum age (t_{max}) is Ps, then rearrangement of the exponential decline in numbers over time (equation 4:2 in FAST) for an unfished population yields the equation presented by Quinn and Desiro (1999):

$$M = -\ln(Ps)/t_{max} \qquad\qquad 4:18$$

where Ps = the proportion of the population that survive to age t_{max}. Quinn and Deriso (1999) suggested using a Ps value of 1%. Shepherd and Breen (1992) reported that using 5% as a proportion surviving to maximum age in 4:18 was preferred by some investigators. Thus, for a population where maximum age was 7 years old, M would range from 0.43 to 0.66 if the

proportion surviving to maximum age was 5% or 1%, respectively. For a population where longevity was as high as 15 years old, M would range from 0.20 to 0.31, respectively.

To estimate M and cm in FAST using the method of Quinn and Deriso (1999), click on the **Run/Analyze** menu then select **Estimate Natural Mortality**. Choose **Quinn and Deriso**, and a window will appear to enter maximum age in years and the proportion surviving to maximum age. Click on **Compute mortality estimates**, and M and cm will be computed and appear at the bottom of the window. These values of M and cm will be associated with the assumption that (Ps * 100)% of the population will reach maximum age in an unfished population.

2) <u>Hoenig</u> - From published literature values and using the same concepts described by Quinn and Desiro (1999) above, Hoenig (1983) obtained instantaneous total annual mortality rates (Z) and maximum ages (t_{max}) from 84 fish stocks representing 53 species that were either very lightly exploited or unexploited populations. Hoenig (1983) assumed overall mortality from these populations approximated M because fishing was nil or very low. By regressing M versus maximum age for these data, the equation was computed:

$$\ln(M) = 1.46 - 1.01 * \ln(t_{max})$$
4:19

The coefficient of determination for equation 4:19 was 0.68, M ranged from about 0.01 to 2.0, and maximum ages ranged from 1 to 80 years old (Hoenig 1983). If natural mortality was high, a species could not survive long enough to obtain an old age. Conversely, for long-lived species that attain older ages, natural mortality would have to be relatively low.

The analyst can use three different methods to estimate maximum age. 1) Use the known maximum age for a species within a region. 2) Use the maximum age observed for the population you are examining. 3) By extrapolation of a catch-curve regression, the maximum age can be estimated if only one individual would hypothetically be collected at that age. This is computed by rearranging Equation 4:5 and substituting one (1) as a number-at-age value to:

$$t_{max} = \ln(1) - b_o/b_1$$
4:20

where b_0 and b_1 are the intercept and slope values from the catch-curve regression. The natural log of one is zero and dividing the absolute value of the intercept by the slope (Z) will estimate maximum age. The **Catch-Curve Analysis** utility in FAST provides this estimate. Hoenig (1983) examined the relation between maximum age and sample size in catch-curve regressions and predicted that maximum age increased with sample size.

To estimate M and cm in FAST using Hoenig's method, click on the **Run/Analyze** menu then select **Estimate Natural Mortality**. Choose **Hoenig**, and a window will appear to enter maximum age in years, then click on **Compute mortality estimates**, and M and cm will be computed and appear at the bottom of the window.

3) <u>Jensen</u> - Typically, long-lived species express a relatively low von Bertalanffy growth coefficient (absolute value of K), while the opposite occurs for short-lived species (Pauly 1980; Jensen 1996). Examining the theoretical relations among age-at-maturity, survival rates to reach maturity, growth in weight, and K, Jensen (1996) proposed natural mortality could be estimated from:

$$M = 1.50*K \qquad\qquad\qquad 4:21$$

This equation was not derived from empirical data and statistical analysis, but rather from fundamental ecological relations among parameters. Typically, as L_4 increases, K will decrease. When deriving the terms for the von Bertalanffy equation in FAST, the analyst can choose to bound the equation with a higher L_4 if the unbounded equation provides a L_4 much less than that observed or known from a population. With higher L_4 infinity values, K will be less, and the use of this K value in equation 4:21 will cause the predicted M to be lower.

To compute M and cm in FAST using the Jensen (1996) method, click on the **Run/Analyze** menu then select **Estimate Natural Mortality**. Choose, **Jensen** and a window will appear to enter the growth coefficient (K, enter positive value), then click on **Compute mortality estimates**, and M and cm will appear at the bottom of the window.

4) <u>Peterson and Wroblewski</u> - Peterson and Wroblewski (1984) derived a size-dependent mortality rate (M), based on mathematical relations among predation, metabolic rate as a function of weight, and growth rate. After hatching, the number of young fish typically declines by four to seven orders of magnitude, and mortality rate of young fish will decrease as size increases (Cushing 1974). Using theoretically derived values, Peterson and Wroblewski (1984) computed the equation:

$$M = 1.92*(WT^{-0.25}) \qquad 4:22$$

where weight (WT) is in grams. Peterson and Wroblewski (1984) compared their equation line for M to values collected for pelagic marine fish from published sources. The line provided a reasonable fit to the data, although a coefficient of determination value was not presented. For some of the fish species we have worked with, equation 4:22 appears to provide reasonable approximations of natural mortality rates when W_4 is used. However, when W_4 is used, this would represent in theory, a minimum natural mortality rate. An analyst could compute M with equation 4:22 using a value for weight when fish reach age-1 or at an age when the population enters the fishery. The effects of this range could then be explored using FAST by entering low and high values of cm. Note from the data listed below, as WT increases, M and cm decrease, but the decline is not proportional to increases in WT because of the low value for the exponent function in equation 4:22.

Weight (g)	M	cm
10	1.08	0.66
50	0.72	0.51
100	0.61	0.46
500	0.41	0.33
1000	0.34	0.29
5000	0.23	0.20

To compute M and cm in FAST using the Peterson and Wroblewski (1984) method, click on the **Run/Analyze** menu then select **Estimate Natural Mortality**. Choose, **Peterson and**

Wroblewski and a window will appear to enter weight in grams. A W_4 value is computed by FAST from terms computed for the von Bertalanffy and weight:length equations and is presented in the lower left corner of the main program window. By choosing a lower weight, a higher rate of M and cm will be computed. Click **Compute mortality estimates**, and M and cm will appear at the bottom of the window.

5) <u>Pauly</u> - Pauly (1980) compiled data for 175 different stocks of fish representing 84 species and used multiple regression to predict M from L_4, K, and mean annual water temperature. Beverton and Holt (1959) and Cushing (1968) showed an inverse relation between K and M that generally demonstrated that slow growing fish tended to live longer and express lower natural mortality rates. Maximum size (length and weight) was also inversely correlated to natural mortality, which may in part be due to size selective mortality (Urshin 1967) and higher metabolic costs incurred by smaller fish (Peterson and Wroblewski 1984). Pauly (1980) speculated that average annual water temperature (TEMP) influenced the M:K ratio and found a significant correlation (r = 0.46, P < 0.01) between water temperature and M when data were transformed to $\log_{10}$ values. Thus, fish from warmer climates expressed a higher rate of natural mortality than fish from colder climates. The correlation between double $\log_{10}$ transformed values for M and K, and M and L_4 were 0.81 and -0.61, respectively. Pauly (1980) computed the following equation:

$$\log_{10}(M) = -0.0066 - 0.279*\log_{10}(L_4) + 0.643*\log_{10}(K)$$
$$+ 0.4634*\log_{10}(TEMP) \qquad\qquad 4:23$$

All variables in this model were significant (P < 0.01) and the coefficient of determination was 0.72. Some multicollinearity was likely apparent in equation 4:23 as a significant relation existed between K and L_4 (r = -0.66, P < 0.01), but multicollinearity diagnostics were not presented by Pauly (1980). Based on beta weight coefficients, the most to least important variables in equation 4:23 were K, water temperature, and L_4.

To compute M and cm in FAST using Pauly's equation, click on the **Run/Analyze** menu then select **Estimate Natural Mortality**. Choose, **Pauly** and a window will appear to enter L_4 in

centimeters, K, and mean annual water temperature in °C. Pauly (1980) suggested that average annual air temperature could be substituted for mean annual water temperature. Click **Compute mortality estimates**, and M and cm will appear at the bottom of the window.

6) <u>Chen and Watanabe</u> - Chen and Watanabe (1989) assumed growth was inversely related to M and rearranged terms from the von Bertalanffy equation, and incorporated life-span information and survivorship curves (see equation 4:1 in FAST manual) to derive an equation to estimate M. From their equation, natural mortality was computed over a range of some initial age to some older or final age. For our examples, we determined that final age should be the maximum age of fish in the population and initial age should be set at age-1. Chen and Watanabe (1989) computed the equation:

$$M(_{t_i \text{ to } t_f}) = (1/t_f - t_i) * \ln(e^{K*t_f} - e^{K*t_o})/(e^{K*t_i} - e^{K*t_o}) \qquad 4:24$$

where t_i and t_f are time of initial ages and final ages, and K and t_o are terms from the von Bertalanffy equation. Similar to previous methods, as longevity increases, M decreases. Chen and Watanabe (1989) compared their predicted values of M to observed M's for seven fish species from the South China Sea, and from their data we computed a coefficient of determination of 0.99.

To compute M and cm in FAST using the Chen and Watanabe equation, click on the **Run/Analyze** menu then select **Estimate Natural Mortality**. Choose, **Chen and Watanabe** and a window will appear to enter **Initial age in years**, **Final age in years** , **K**, and t_o. We recommend for the **Yield-per-recruit** model that initial age be set to age 1 and final age be set to maximum age. In the **Dynamic pool model**, the analyst can choose a number of different age-specific cm rates. If the analyst chooses to compute a natural mortality rate with initial age greater than age 1 while holding final age or maximum age constant, M and cm will decline slightly which would suggest that mortality rates for older fish is less than for younger fish. Click **Compute mortality estimates**, and M and cm will appear at the bottom of the window.

From each of these six methods, we computed and compared cm rates for three of our example populations located in the **Sample file** directory (Table 4-5). For sauger which had a relatively short life span, a high K value, and lower maximum size, cm ranged from 0.26 to 0.50 for all six methods. As expected, the estimates of cm were generally lower for largemouth bass and striped bass which are longer lived, reach larger sizes, and expressed lower K values. Maceina et al. (1998) used cm rates of 0.25 and 0.40 when conducting simulation modeling of this sauger population. These rates were chosen based on estimates of exploitation and "best guesses" from previous experience. For largemouth bass, cm ranged from 0.21 to 0.32 similar to values used to analyze this population (see Chapter 9). Overall annual mortality was 39% based on catch-curve analysis from this population and exploitation likely ranged from 5 to 10% per year (Maceina, unpublished data). Thus, these cm rates appear reasonable. Finally, these six methods predicted cm rates of 0.10 to 0.18 for striped bass from the Chesapeake Bay. Richards and Rago (1999) indicated a cm rate of 0.18 was used in the management decision process for this population.

These six methods provided approximate estimates of natural mortality consistent with previous analyses and collection of other data for our examples. Pauly's (1980) equation predicted the highest cm rates, while the Peterson and Wroblewski (1984) equation generally predicted the lowest cm rates. In freshwater populations, Pauly's (1980) equation may over predict M due to the inclusion of L_4 as an independent term. We suspect predation risk of larger individuals is greater in marine than in freshwater systems.

Table 4-5. Predicted rates of conditional natural mortality (cm) derived from six methods for three species presented as examples in the **Sample file** directory of FAST. These six methods include 1) Quinn and Deriso (1999), 2) Hoenig (1983), 3) Jensen (1996), 4) Peterson and Wroblewski (1984), 5) Pauly (1980), and 6) Chen and Watanabe (1989).

		L4 (cm)	k	to	W4 (g)	Temp (ºC)	tmax (years)	Method (cm rate)					
								1	2	3	4	5	6
FAST file name (.par)	Species												
Tenn_River_Sauger	Sauger	55.0	0.401	-0.582	1,746	19	10	0.26 to 0.37	0.34	0.45	0.26	0.50	0.38
Eufaula_LMB_1997-99	Largemouth bass	62.3	0.164	-1.530	4,150	21	13	0.21 to 0.30	0.28	0.22	0.21	0.32	0.22
Striper_CB_1995	Striped bass	135.0	0.111	0.065	45,158	14	30	0.10 to 0.14	0.13	0.15	0.12	0.18	0.17

<u>The customized mortality option in FAST</u>

    For many modeling scenarios, fixed mortality rates are preferred in order to maintain simulated populations in steady-state, equilibrium conditions. However, situations arise that require the ability to change mortality rates during the course of a simulation. Such a situation might be the simulation of a fishery that instituted for example a two year moratorium on fishing, then returned to some level of fishing mortality.

    The **Dynamic Pool** model offers an option to allow the analyst to set the conditional fishing and conditional natural mortality rates by age for each year of a simulation. This allows greater flexibility in performing a simulation analysis. This option can be used in conjunction with the **Customized Recruitment** option (see Chapter 5) to structure a population over the course of a multi-year simulation. Additionally, this option allows for the computation of transitional and weighted transitional SPR values which are computed on a yearly basis (see Chapter 5).

    Structuring a population in this way is similar to Virtual Population Analysis (VPA) in that both methods rely on age-specific estimates of fishing and natural mortality. However; in contrast to VPA which calculates past population abundances on the basis of past catches at age, the Customized Recruitment and Customized Mortality options in FAST can be used to calculate future population abundances from past recruitment levels. If past recruitment levels for a population are unknown, but harvest levels have been monitored for some time, VPA could be used to compute past recruitment levels that could then be used in the Customized Recruitment option of FAST.

    Age-specific mortality rates are entered by selecting the **Customized Mortality** option button in the Mortality Options frame of the Dynamic Pool main window. This action will open an embedded spreadsheet similar to the one pictured below. The first column of the spreadsheet will show the number of years that were entered in the **Num Years** text box in the Model Parameters frame, and the first row will contain the number of ages that were entered in the **Max Age** text box. The spreadsheet contains two worksheets: one named **cf** (conditional fishing mortality) and the other named **cm** (conditional natural mortality). Once this is done, the age-specific mortality rates (cf and cm) can be entered for each year of a simulation.

    As mentioned in Chapter 6, the value entered for the minimum length limit takes precedence

over the age with respect to fishing mortality when the model is run. For example, if a value of 0.25 was entered for conditional fishing mortality between age-0 and age-4, but the time to reach the minimum length limit was 3.5 years, the effects of fishing mortality would not occur until that time and only the force of natural mortality would remove fish from the population between age-0 and age-3.5.

In the worksheet above, **cf** changes from 25% to 10% in the eleventh year of the simulation. Again, although a **cf** value is present for all ages, no fishing mortality will be exerted on the population until it reaches the minimum length limit. So if fish in this example reached the minimum length at age-2.4, no fishing mortality would occur for age-0 or age-1 fish, even though values of **cf** have been assigned to these ages in the worksheet. Once fish have reached the minimum length limit, they become subject to the force of fishing mortality defined by the values entered in the worksheet. If a spreadsheet cell is left blank, it is treated as a zero (i.e., no mortality).

5. RECRUITMENT

<u>Background</u>

Recruitment of young fish into catchable, harvestable, or adult size is necessary to sustain any capture or recreational fishing if stocking does not take place. Recruitment failure, due either to over fishing, habitat alteration, or major abiotic or biotic events will ultimately lead to reduced adult abundance and lower angler catch rates in the fishery. Conversely, if reproduction is high, density-dependent mortality is not excessive, and growth rates remain adequate to permit recruitment into the fishery, then adult abundance will increase and fishing success will be greater.

Due to a number of factors, recruitment success typically varies from year to year. Some species from certain populations may display fairly constant recruitment each year, whereas other species or populations have highly erratic recruitment that may cause wide fluctuations in the number of fish reaching a certain age. The processes and mechanisms forming weak and strong year classes in fish populations have been intensively studied over the years. An analyst can incorporate recruitment variability into the FAST modeling procedures to predict the impact of recruitment variability on a fishery including parameters such as population abundance, harvest rates, yield, size of harvested fish, number of fish of certain length groups, and length-structure indices.

In the 1980's, marine fishery scientists attempted to quantitatively address the problem of recruitment over fishing and developed a simple index termed the spawning potential ratio (Goodyear 1993). Typically, recruit:parental relations to define a critical abundance of spawning adults using Ricker or Beverton-Holt equations (Hillborn and Waters 1992) have been wrought with high variability and confounding effects of environmental factors that affect recruitment (Goodyear and Christensen 1984; Goodyear 1993; Hansen et al. 1998). In addition, long-term (> 20 years) data that are usually necessary to define recruit:parent relations require extensive planning, commitment to sample, and can be expensive to collect.

The spawning potential ratio (SPR) is simply the fraction of mature eggs produced at a certain level of exploitation (numerator) for a given population divided by total number of eggs produced in the population if no fish were exploited. Target SPR's can be achieved by protecting

mature females with either length or bag limits or with the use of protective slots, or with closed seasons or closed fishing grounds. The SPR is used as a management criteria to maintain adequate females in the population to prevent recruitment over fishing.

Although critical values for the SPR have not been defined nor used to evaluate sport fisheries, exploring their utility warrants investigation. For example, management strategies to maintain white sturgeon *Acipenser transmontanus* in the Columbia River (Oregon-Washington) include protecting older mature females that can be caught and released using hook and line gear, but allow harvest of a slot length (92 to 183 cm) of smaller fish (Rieman and Beamesderfer 1990). In the upper Mississippi River, increasing the minimum length limit on channel catfish *Ictalurus pucnctatus* from 33 to 38 cm led to a corresponding increase in age-0 production (Pitlo 1997). Typically, mature ova production increases exponentially with fish length, and in some instances larger females in a population can produce one to two orders of magnitude more eggs then younger sexually mature fish. FAST provides the analyst the capability to compute the SPR.

Computation of recruitment variability using sampling methods

Fishery biologists collect long-term monitoring or research data that can be used to estimate recruitment variability. For a particular species or population, the analyst must decide what time in the early life of a fish is critical for recruitment to the fishery. For example, Sammons and Bettoli (1998) showed low and high larval abundance of white bass *Morone chrysops* and crappie *Pomoxis* spp. ultimately lead to corresponding weak and strong year class formation a few years later. Maceina and Stimpert (1998) used trap net catch rates of age-1 crappie in the fall as a index of recruitment variability. Bettoli et al. (1992) found abundance of age-1 largemouth bass *M. salmoides* collected in the spring with cove rotenone sampling corresponded to year-class strength establishment. Wright (1991) used electrofishing to describe variability in catch rates of age-1 largemouth bass over a ten-year period.

Allen and Pine (2000) reviewed published and unpublished data on recruitment variability in crappie and largemouth bass based on age-0 and age-1 catch rates using trap nets, electrofishing, and rotenone. Coefficients of variation (CV; standard deviation/mean) for recruits averaged 82% (range 55 - 124%) for crappie and 66% (11-189%) for largemouth bass. These average values

for recruitment variability will cause populations and associated catch statistics in the fishery to fluctuate drastically. These fluctuations can be demonstrated by the analyst using FAST.

Typically, any sampling method with catch rates standardized to some unit of effort or area (for population estimates) can be used to measure recruitment variability. These samples should be taken at about the same time each year, and ideally during similar environmental conditions. In some instances, fixed or permanent stations are used that serve as replicates. When attempting to detect statistical differences over time with fixed stations, repeated-measures analysis of variance should be used (Maceina et al. 1994). Random sampling schemes can be employed to measure juvenile fish abundance, but spatial variability may be greater than year-to-year variability, and therefore, more replicate samples may need to be taken.

Examples of data are presented below that illustrate the type of information that can be used to measure recruitment variability. In Table 5-1, crappie were sampled in two reservoirs using trap nets in the fall of each year from 1990 to 1999 at the same stations. Total trap net effort was 40 and 76 net-nights in Jones Bluff and Weiss reservoirs, respectively. Ages were determined by otolith examination (Maceina and Betsill 1987), and both age-0 and age-1 catch-per-effort (N/net-night) and corresponding means, standard deviations, and CV's were computed. Data are from Maceina and Stimpert (1998) and Maceina (unpublished data).

Table 5-1.

Year class	Weiss Reservoir		Jones Bluff Reservoir	
	Age-0 CPE	Age-1 CPE	Age-0 CPE	Age-1 CPE
1989	--	3.12	--	2.78
1990	8.03	5.32	12.93	8.10
1991	0.47	0.39	2.35	2.55
1992	0.61	0.97	7.93	4.15
1993	1.38	3.59	13.80	6.58
1994	2.73	2.61	3.48	1.10
1995	1.66	0.57	3.48	3.65
1996	9.89	8.63	23.70	11.03
1997	1.86	0.93	3.75	0.85
1998	3.72	1.17	15.53	5.63
1999	2.18	--	11.23	--
Mean	3.25	2.73	9.81	4.64
Standard Deviation	3.18	2.61	6.90	3.22
Coefficient of variation	98%	96%	70%	69%

For these data sets, recruitment variability was slightly higher in Weiss Reservoir, but the CV's for age-0 and age-1 catch rates were similar within reservoirs. About a 20-fold difference between minimum and maximum catch was observed in Weiss Reservoir compared to about a 10- fold difference in values from Jones Bluff Reservoir.

Abundance of age-0 walleyes *Stizostedion vitreum* was estimated each year from 1958 to 1996 using electrofishing and a Schnabel mark-recapture method each September-October in Escanaba Lake (119 ha), Wisconsin (data presented in Hansen et al. 1998; Table 5-2).

Table 5-2.

Year-class	Age-0 walleyes (N/ha)
1958	38
1959	193
1960	5
1961	7
1962	124
1963	111
1964	267
1965	89
1966	187
1967	73
1968	74
1969	159
1970	85
1971	29
1972	14
1973	211
1974	118
1975	16
1976	19
1977	146
1978	45
1979	58
1980	9
1981	137
1982	52
1983	87
1984	141
1985	123
1986	129
1987	117
1988	37
1989	36
1990	299
1991	41
1992	104
1993	165
1994	254
1995	35
1996	11
Mean	99
Standard deviation	77
Coefficient of variation	78%

This long-term data base is very useful for understanding the dynamics of walleye recruitment in Escanaba Lake, but represents a tremendous amount of sampling effort over a very long time period that obviously cannot be achieved for every fishery. The CV was relatively high and a 60-

fold difference occurred between minimum and maximum densities of age-0 walleye.

In Lake Guntersville, Alabama, age-1 largemouth bass were collected from the same locations with electrofishing each spring from 1991 to 1995 (Wrenn et al. 1996; Table 5-3). In Lake Eufaula, Alabama, fishery biologists from the Alabama Department of Conservation and Natural Resources (K. Weathers unpublished data) collected largemouth bass from randomly chosen stations each spring from 1991 to 2000. Catch-per-effort were reported as number of age-1 fish per hour of electrofishing.

Table 5-3.

Year-class	Guntersville N age-1/hr	Eufaula N age-1/hr
1990	20	22
1991	6	8
1992	31	35
1993	29	17
1994	7	10
1995	-	61
1996	-	23
1997	-	4
1998	-	99
Mean	18.6	31.0
Standard deviation	11.8	30.8
Coefficient of variation	63%	99%

Ideally, long-term collection and computations of young fish abundance to estimate recruitment variability would be available. However, long term data sets similar to that in Table 5-2 or even short term data presented in Tables 5-1 and 5-3 may not even be available. To assess the uncertainty of the impact of a proposed length limit on the fishery over time when weak and strong year-class formation occurs, catch-curve regressions can provide an estimate of recruitment variability. The advantage of this method is that only a single large sample of fish is needed. However due to a host of assumptions, this method only provides a crude estimate of recruitment variability and data from the long-term collection of young recruits is more desirable.

Guy and Willis (1995) used catch curves to identify missing year classes and developed a qualitative recruitment variability index that described stability in annual cohort production. Maceina (1997) built upon this concept by expanding simple linear catch-curve regression to a multiple regression by including an environmental variable related to the formation of weak and strong year-classes. Observed values above and below the catch-curve regression line represent above and below average year-class production, respectively (Maceina 1997). The higher the absolute value of the residuals or deviations from the regression line, the greater the magnitude of year-class formation.

Static Spawning Potential Ratio (SPR)

Goodyear (1993) provides a comprehensive review of the SPR. Goodyear (1993) defined potential recruit fecundity (P) as then number of mature eggs that could be produced by an average recruit in a population where density-dependent growth and survival did not occur. P represents the actual average lifetime production of mature eggs per recruit at equilibrium population densities in the absence of any density-dependent suppression of maturation or fecundity at age. P is determined (Goodyear 1993) from:

$$P = \sum_{i=1}^{n} E_i \prod_{j=0}^{i=1} S_{ij}$$ 5:2

where:
   n = number of ages in the unfished population;
   E_i = mean fecundity of females of age i in the absence of density-dependent growth;
   $S_{ij} = e^{(-(Fij + Mij))}$, the density-independent annual survival probabilities of females of age i when age j;
   F_{ij} = the fishing mortality rate of females of age i when age j; and
   M_{ij} = the natural mortality rate of females of age i when age j.

Exponential functions for fishing mortality (F) and natural mortality (M) are incorporated into this integral equation similar to predicting cohort abundance from survival over time as presented

in equation 4:8. If natural mortality is very high, exploitation would have removed some fish that would have died anyway and not contributed to the lifetime cohort production of eggs.

The SPR is defined as:

$$SPR = P_{fished}/P_{unfished} \qquad\qquad 5:3$$

The SPR has a maximum value of 1.00 (unity) and declines towards zero as fishing mortality increases. Goodyear (1993) recommends SPR targets of no less than 20 to 30% based on observations of pelagic marine species. He further stated that the use of SPR provides a conservation strategy to maintain adequate reproduction in the stock that is independent of attempting to predict maximum sustained yield. Mace and Sissenwine (1993) reviewed 91 recruit-parent relations for commercially exploited species in North America and Europe and found critical minimum SPR values as low as 20% for some species (high resilience to fishing), but as high as 40 to 60% for some small pelagic species (low resilience to fishing).

Transitional spawning potential ratios

In the preceding section, SPR was calculated on a per-recruit basis assuming equilibrium conditions of recruitment and mortality. This measure of SPR is known as a static SPR since it is computed without regard to annual changes in population structure or mortality rates. Alternatively, transitional SPRs are computed on a yearly basis and take into consideration annual variation in population structure and mortality rates. Transitional SPRs are further divided into two sub-categories: un-weighted transitional SPR (hereafter referred to as transitional SPR) and weighted transitional SPR. A comprehensive review of the similarities, distinctions, and uses among the three forms of SPR has been provided by Parkes (2001), and only a brief summary will be made here.

Unlike static SPR, transitional SPR (tSPR) can be considered a dynamic measure of SPR. Although computationally similar to static SPR, tSPR is calculated using actual annual estimates of population numbers and fishing mortalities. Therefore, it is a measure of the actual *per capita* reproductive output that occurred over the lifespan of recent cohorts, relative to that which would

have occurred if those cohorts had never been fished (Parkes 2001). Unlike static SPR, which is directly proportional to fishing mortality, tSPR corresponds to a moving average of fishing mortality rates.

Weighted transitional SPR (wtSPR) is similar to tSPR with the exception that it is weighted by the absolute size of the year-classes in the population. It therefore provides a measure of the actual *realized* reproduction from each cohort in a given year as a fraction of the reproduction that would have occurred if those cohorts had never been fished (Parkes 2001).

To calculate tSPR, the number of female fish at each age in each year are multiplied by the by the number of eggs produced by those fish at each of the ages to give the total number of eggs produced at each age. Next, the total number of eggs at each age in a given year are divided by the number of recruits which produced that age class of fish. For wtSPR, the number of eggs at each age are not divided by the number of recruits that produced that age class of fish. These calculations are done twice: once for a population that has been fished and then for a population that has not been fished. The result from the fished population is then divided by the result from the unfished population.

Equations for static SPR, tSPR, and wtSPR are provided below using the following notation (Parkes 2001). Note that the equation for static SPR, while different from that of Goodyear (1993), is computationally similar.

t $\quad$ = year
r $\quad$ = age of recruitment into the fishery
G $\quad$ = maximum age of fish in the stock
$N_{i,t}$ = number of fish of age i at the beginning of year t
$P_{i,t}$ = per capita reproductive output of fish of age i at the beginning of year t
$M_{i,t}$ = natural mortality rate of fish of age i at the beginning of year t
$F_{i,t}$ = fishing mortality rate of fish of age i at the beginning of year t
$Z_{i,t}$ = total mortality rate of fish of age i at the beginning of year t (= $F_{i,t} + M_{i,t}$)

Static SPR = $\dfrac{\displaystyle\sum_{i=r}^{G}\left\{P_{i,t}\prod_{\substack{j=r\\i\neq r}}^{i=1}\left[\exp(-Z_{i,t})\right]\right\}}{\displaystyle\sum_{i=r}^{G}\left\{P_{i,t}\prod_{\substack{j=r\\i\neq r}}^{i=1}\left[\exp(-M_{i,t})\right]\right\}}$ $\qquad$ 5:4

Unweighted transitional SPR = $\dfrac{\displaystyle\sum_{i=r}^{G}\left\{P_{i,t}\prod_{\substack{j=r\\i\neq r}}^{i=1}\left[\exp(-Z_{i,t-i+j})\right]\right\}}{\displaystyle\sum_{i=r}^{G}\left\{P_{i,t}\prod_{\substack{j=r\\i\neq r}}^{i=1}\left[\exp(-M_{i,t-i+j})\right]\right\}}$ $\qquad$ 5:5

Weighted transitional SPR = $\dfrac{\displaystyle\sum_{i=r}^{G}\left\{N_{r,t-i+r}P_{i,t}\prod_{\substack{j=r\\i\neq r}}^{i=1}\left[\exp(-Z_{i,t-i+j})\right]\right\}}{\displaystyle\sum_{i=r}^{G}\left\{N_{r,t-i+r}P_{i,t}\prod_{\substack{j=r\\i\neq r}}^{i=1}\left[\exp(-M_{i,t-i+j})\right]\right\}}$ $\qquad$ 5:6

<u>Using FAST to compute fecundity-to-length relation</u>

To compute SPR with FAST, a fecundity-to-length relation must be provided. FAST can compute this relation from paired data of length (mm) and number of eggs for individual fish. Two fecundity-to-length relations can be computed: a linear relation or a double $\log_{10}$ transformed relation.

From the menu bar on the main window of either the **Yield-Per-Recruit Model** or the **Dynamic Pool Model**, click on **Run/Analyze** and select **Fecundity-Length Regression**. An embedded spreadsheet will appear (for an explanation of the spreadsheet module used in FAST, see Chapter 11 of this manual). Data must be properly entered into the first sheet of the spreadsheet. The first row must contain column headers as text, with the associated numerical data entered in the rows beneath the header row. By default, the Input sheet is shown and in column A, enter the length (mm) and in column B, enter the fecundity (number of eggs). For this procedure, the analyst should have already estimated the number of eggs for each fish.

To save the data in a .vts file, click on **Activate Worksheet**, and save the file as you would in any other spreadsheet application. Close the **Activate Worksheet** window, the data will reappear, then click on **Run Regression**. Two choices, **linear** and **$\log_{10}$ transformed** are provided. By clicking on one of these, the regression is computed and results given.

A sample file (**lmb_f-l.vts**) is provided in the sample files folder that contains number-at-age data from a sample of 134 adult, female largemouth bass from Lake Seminole, Georgia, collected with electrofishing in spring1998. The **Length** variable is the total length (mm) and the **Fecundity** variable is the number of eggs $\geq$ 1 mm in diameter. To compute a fecundity-to-length regression for these data, activate the spreadsheet and open this file. Close the active spreadsheet to return it to its embedded form then click on **Run Regression**. Two choices, linear and $\log_{10}$ transformed regressions are provided. By clicking on one of these, the regression is computed and results provided in a spreadsheet similar to the one depicted below.

Fecundity-Length Regression

Run Regression   View Plot   Spreadsheet   Return to Main Window

| A1 | | Length-Fecundity Regression Results |

	A	B	C	D	E	F	G
1	Length-Fecundity Regression Results						
2	Analysis Of Variance Table						
3							
4			Sums of	Mean			
5	Source	DF	Squares	Square	F-value	Prob > F	
6	Model	1	1.2E+010	1.2E+010	91.712659	0.0001	
7	Error	132	1.7E+010	1.3E+008			
8	Total	133	2.9E+010				
9							
10	R-squared						
11	0.4099574						
12							
13	Variable	Estimate					
14	Intercept	-42409.42					
15	Slope	144.91238					
16							

ANOVA Table   Residuals   Input

Interpretation of the FAST output for fecundity-to-length regression

The output regression ANOVA table after running either the linear or $\log_{10}$ transformed regression is very similar to most outputs for other statistical packages. Model, error, and total degrees of freedom, sums of squares, mean squares, an F-value, and a probability associated with the F-value are given. Examination of both regressions shows that the statistical probability value for this example is 0.0001, and indicates that both the linear and $\log_{10}$ transformed regression equations are significant and the null hypothesis that the slope of the line between Fecundity and Length or Log_{10}(Fecundity) and Log_{10}(Length) is equal to zero can be rejected. The r-square value, and the intercept and slope of the regression are given. Examination of both regressions indicates that while both models are highly significant, the linear model has a higher F-value and explains 3% more of the variation in the dependent variable than does the $\log_{10}$ transformed model. The parameter estimates from the linear model indicate that on average, for each 1 mm increase in fish length, 145 additional eggs are produced. The intercept and slope parameters can be entered into the Reproduction Options window when performing a SPR analysis.

To graphically view the results of the catch-curve analysis, click **View Plot**. Depending on the regression model that was chosen, a linear or logarithmic plot of fecundity against length is displayed. From the Plot window, click on **View Chart** to visualize the residual plot for the regression.

<u>Using FAST to compute spawning potential ratios</u>

FAST can compute the static SPR for different levels of fishing mortality over a range of minimum length and slot length limits for given natural mortality rates. Static SPR is computed using the **Yield-Per-Recruit** model. In the upper central area of the main menu in the middle near the top is a window entitled **Compute SPR?**. The default is **No**. Click **Yes** and another window appears that requires data to compute SPR. Fecundity is predicted from length and this relation can be described with FAST or with another statistical package. FAST provides the option of using two regressions to predict fecundity from length. For the option that is titled **Is the Fecundity-Length Relation Logarithmic or Linear?**, regression coefficients for double $\log_{10}$ transformed or linear data are entered. **Age of Maturation** is the first age that females become mature and contribute to offspring production. If only a fraction of females become mature at the earliest age of maturation, this can be adjusted in the next set of boxes. In **Age-specific Reproduction**, the analyst can enter **percent (%) of all fish that are females** and **percent (%) of all females spawning annually** for six different age groups. This window allows the analyst to account for changes in sex ratios that can occur in populations over time, as well as changes in the number of females contributing to the total reproductive potential of the population in any single year.

To compute tSPR and wtSPR, the **Dynamic Pool** model is used. By selecting the **Yes** option in the **Compute SPR?** frame, the Reproduction Options window as described above is displayed. The **Customized Recruitment** and **Customized Mortality** (see Chapter 4) options of FAST can be used to structure a simulated population to obtain desired numbers-at-age for use in the computation of tSPR and wtSPR. These measures are computed for each year of the simulation once full recruitment to the population has taken place (e.g., for a 50 years simulation on a population with a maximum age of 20 years, tSPR and wtSPR are computed for years 21 to 50). It should be noted that if recruitment is held constant throughout the simulation period, the two measures will produce identical results. Additionally, if recruitment and mortality rates (fishing and natural) are held constant during the simulation period, these measures will produce results identical to the static SPR calculated using the Yield-per-Recruit model. A thorough example of using static SPR, tSPR, and wtSPR analyses is presented in Chapter 10 of this manual.

Using FAST to predict impact of recruitment variability on the fishery and population

Upon opening FAST, choose the **Dynamic Pool Model** option. Data are computed for each age up to the maximum age of the population and the total number of years to be simulated. Thus, individual year classes starting at age-1 can be tracked over time at different levels of recruitment. For example, in a population that has a maximum age of 7 and simulated over a 100 year period, a total of 700 observations are computed. In the upper right side on the main window, six different recruitment options are provided for the analyst in the frame entitled **Variable Recruitment Options**.

1) By clicking on **Fixed**, the rate of age-0 recruits is the same for each year the population is simulated. By default, 1,000 age-0 recruits appears. This recruitment option can be used to vary recruitment from year-to-year by changing the input and can incorporate density- dependent growth and survival. For example, the analyst could assume 1,000 recruits was a long-term average, but a five-fold increase in age-0 recruits could lead to lower growth rates and higher natural mortality. If growth data was available for this year class over time, new von Bertalannfy and weight:length relations would be entered, and survival adjusted. Below the **Variable**

Recruitment Options frame is another frame that contains **Mortality Options**. For example, a natural mortality rate of 90% for 1,000 age-0 recruits yields 100 age-1 recruits. In the **Age 0 to Age** box under **Mortality Options** enter 1 to denote Age 1 and enter 0.9 for the **cm** and leave the **cf** box blank.   If the analyst should chose 5,000 age-0 recruits and the natural mortality rate was 96% due to density-dependent mortality, for example, then 0.96 would be entered in the **cm** box and this would confer 200 age-1 recruits.

2) The next option in the **Variable Recruitment Options** is **Random (uniformly distributed***)*. This option provides the analyst with two boxes to enter the minimum and maximum values of an index of recruits. The number of recruits produced each year is then randomly chosen between the minimum and maximum values. An option is available to choose whether the same set of random numbers is used each model run, or if a different set of random numbers is computed for each run. For example, minimum and maximum catch-per-efforts of age-1 largemouth bass from Lake Eufaula were 4 and 99 per hour (Table 5.3) and these values would be entered in the corresponding boxes.
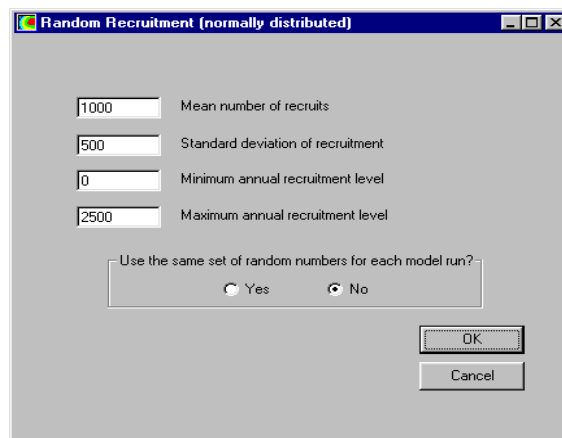
These data were collected in spring of each year and the analyst could assume that year-class strength was fixed at this time, but this may not be true. In the **Mortality Options** section for this data set enter a zero for **cm** (no natural mortality) in the **Age 0 to Age** box. A value of 1

placed in the box next to **Age** would compute the number of age-1 recruits. When estimating

numbers of age-1 fish from mortality between age-0 and age-1, the response of the population

will be the same except the number of age-1 and older fish will be lower or higher depending on

the natural mortality rate. However, the percent differences between any length or bag limitation

of the predicted response of the fishery will be the same if natural mortality is held constant for

different simulations.

When ready to simulate the population under this variable recruitment option, enter the

number of years to model in the **Num Year** box in the **Model Parameters** frame on the lower

left side of the main window. When FAST runs this variable recruitment option, the

distributions of recruits are uniformly computed between the minimum and maximum recruits

that were entered in this option. For the age-1 largemouth bass catch data from Lake Eufaula

presented in Table 5.3, the predicted distribution of recruits over a 100 year simulation are

presented below. A perfectly uniform distribution will rarely be computed because a random

numbers generator is used in the computations.
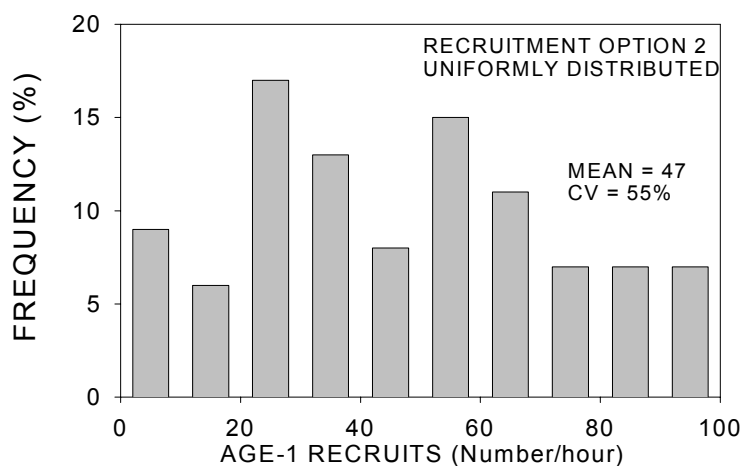
3) The **Random (normally distributed)** variable recruitment option computes a series of age-0 recruits based on a random deviate from a normal bell shaped distribution.   FAST by default displays a **Mean number of recruits** of 1,000, a **Standard deviation of recruits** of 500, a **Minimum annual recruitment level** of 0, and a **Maximum annual recruitment level** of 2,500. An option is available to choose whether the same set of random numbers is used each model run, or if a different set of random numbers is computed for each run. The CV for age-0 crappie collected with trap nets from Jones Bluff Reservoir (Table 5-1) was 70%. In these two boxes, the analyst could leave the **Mean number of recruits** at 1,000, but change the **Standard deviation of recruits** to 700 which would represent a CV of 70%. If the analyst desired to lower the number of recruits entering the population for scaling purposes, then for example, a mean of 100 could be entered with a standard deviation of 70.

    Using the example for age-0 crappie from Jones Bluff, the values of 1,000 and 700 are entered for the mean and standard deviation under this recruitment option, minimum recruitment level was left at zero, maximum recruitment level was set at 5,000, and conditional natural mortality was set at 90% from age 0 to age 1 in the **Mortality Options** frame. Hence, if the mean number of age-0 recruits was set at 1,000, an average of 100 age-1 recruits would enter the population each year.   The corresponding distribution of age-1 recruits is plotted for a 100 year simulation by choosing 100 in the **Num Years** box in the **Model Parameters** frame. Note below that the computed CV for this 100 year simulation was 66%, slightly less than the input CV of 70%.

RECRUITMENT OPTION 3
RANDOM NORMALLY DISTRIBUTED

MEAN = 99
CV = 66%

FREQUENCY (%) vs. AGE-1 RECRUITS (Number/net-night)
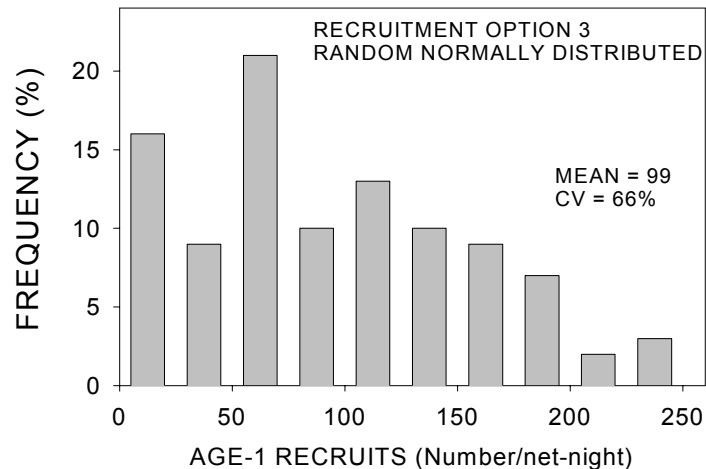
As the value of the input CV for recruitment increases, the computed output CV's for recruitment will decline slightly. This is because FAST uses two random numbers generators and a table of standard normal distribution areas for the **Random (normally distributed)** recruitment option. The first random numbers generator computes values between 0.0 and 0.4990 each simulation year. The resulting value is compared to the values in the normal distribution table to determine the z-value (number of standard deviations from the mean). The second random numbers generator determines whether the deviation from the mean is positive or negative. As an example, suppose the first random numbers generator produced a value of 0.4332, and the second random numbers generator produced a negative value. Examination of any normal distribution table will show that 0.4332 is associated with a z-value of 1.5. If the analyst had chosen a mean recruitment level of 1000 recruits and a standard deviation of 500, the number of recruits produced for this example year would be 1000 - (500*1.5) = 250.

A normal distribution table shows a maximum z-value of 3.09. Therefore, when the analyst enters a standard deviation that is greater than approximately 30% of the mean, the potential exists to produce values that would result in a negative number of recruits for a given year. As an example, suppose the analyst had chosen 1000 as the mean and standard deviation in the previous example. The resulting number of recruits for that year would be 1000 - (1000*1.5) = -500. Obviously, a negative number of recruits is not valid, so FAST converts negative values of recruits to the **Minimum annual recruitment level** when this occurs. Similarly, the maximum

5-18

number of recruits produced each year can be bounded by the value entered in the **Maximum annual recruitment level** box. Therefore, the number of recruits produced using this option will follow a true normal distribution only when the coefficient of variation (CV = standard deviation/mean) chosen by the analyst is less than or equal to 30% of the mean. Additionally, the deviation from normality will increase proportionally with higher CV's.

Using the **Random (normally distributed)** recruitment option in FAST, 1,000 year simulations were conducted by varying recruitment CV's from 10 to 120% at 10% increments. The default value of 1,000 for **Mean number of recruits** was used and conditional natural mortality was set at 0.9 from age 0 to age 1. The **Minimum annual recruitment level** was set to zero and the **Maximum annual recruitment level** was set to 5,000 so it would not be reached. For each simulation, the computed number of age-1 recruits was observed in the spread sheet provided by clicking on **View Output**, then **Tabular Model Output by Year**. At the bottom of the spreadsheet, the mean number of age-1 recruits and associated standard deviations are provided. From this, the computed recruitment CV's were plotted against input recruitment CV's (Figure 5-2). Computed recruitment CV's were nearly identical to input recruitment CV's up to 60%. At higher input CV's, computed CV's were lower because disproportionately more values of zero were derived for the number of age-1 recruits because the number of age-1 recruits cannot be a negative value. Similarly, when input recruitment CV's exceeded 70%, the simulated average number of age-1 recruits increased slightly above the expected value of 100 (Figure 5-2). Again, this occurred because FAST does not compute negative values for the number of age-1 recruits. This analyses provides the users with some insights into the impact of high recruitment CV's on populations when interpreting FAST output.

When using the catch-curve technique presented earlier (Chapter 4) to estimate recruitment variability, we recommend the coefficient of determination from the unweighted catch-curve regression option be used. From the catch-curve results presented in Chapter 4 for smallmouth bass, annual mortality was 41.5%, the age range was 9 years, and the coefficient of determination was 0.775. Placing these values into the regression equation 5:1 predicts a recruitment CV of 51%. If the **Mean number of recruits** was 1,000 for this option, then 510 should be entered in the **Standard deviation of recruits** box.
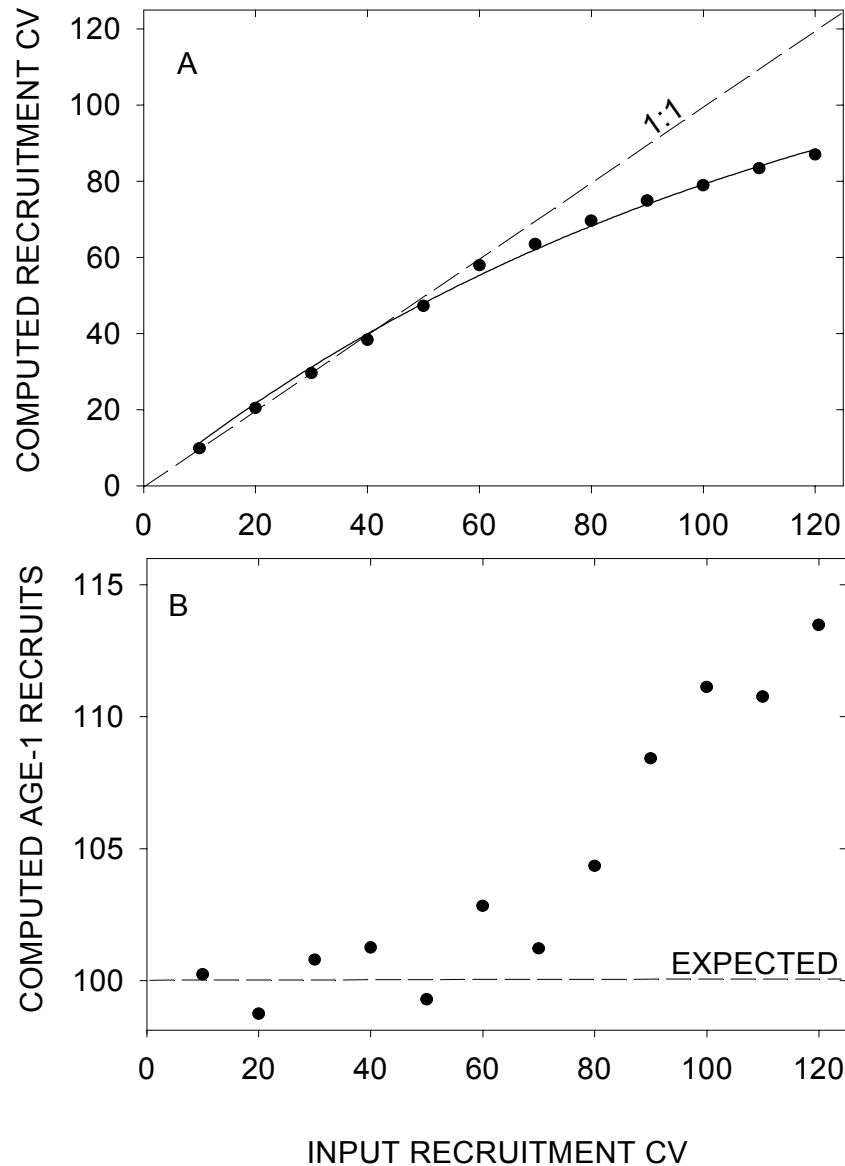
Figure5-2. Input recruitment coefficients of variation (CV) entered in the ***Random (normally distributed)*** option in FAST plotted against the computed recruitment coefficients of variation for a 1,000 year simulation (A).   Input recruitment CV's from the same option plotted against the average number of computed age-1 recruits for a 1,000 year simulation (B). The expected average number of age-1 recruits for each input recruitment CV was 100.

4) Another variable recruitment option can be computed by using **Strong year-class every Nth year**. FAST uses four variables to compute this option.

Interval (years) is the time interval between strong year-class formations (default value is 5 years). The **Year of first strong year class** can be any year between the first year and the value entered in **Num Years** in the Model Parameters frame (default value year 5). **Size of average year-class** is the average number of age-0 recruits and the default value is set at 1,000. **Size of strong year class (times avg)** is a multiplier of the average number to compute a higher number associated with the strong year-class (default value is 2). Thus, for the default recruitment option, a strong year class of 2,000 individuals is produced every 5 years and will be evident at year 5, 10, 15, and will continue for as many years that are chosen to run the simulation. The plot below used the default values and a conditional natural mortality of 90% between age-0 and age-1.
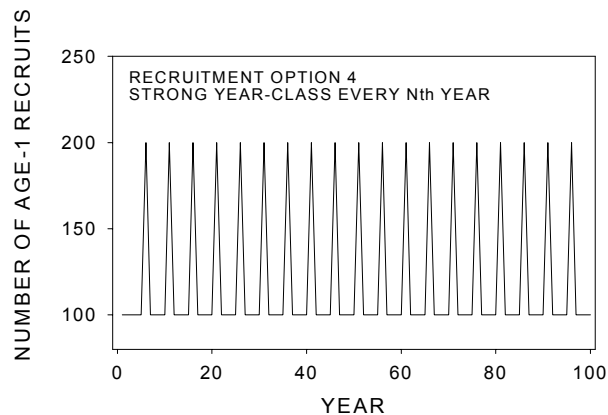
5) **Strong year-class at random intervals** is the fifth variable recruitment option. FAST uses three variables to compute this recruitment option.

Average frequency (years) of strong year-classes is similar to the first variable for the previous option except that the frequency of strong year-class formation is randomly chosen about the average frequency based on a random numbers generator (default value is 5 years). An option is available to choose whether the same set of random numbers is used each model run, or if a different set of random numbers is computed for each run. **Size of average year-class** and **Size of strong year class (times avg)** are similar to the last recruitment option, with default values set at 1,000 and 2. For a 100 year simulation, a graph of age-1 recruits over time when conditional natural mortality was 90% between age 0 and age 1 is presented below.
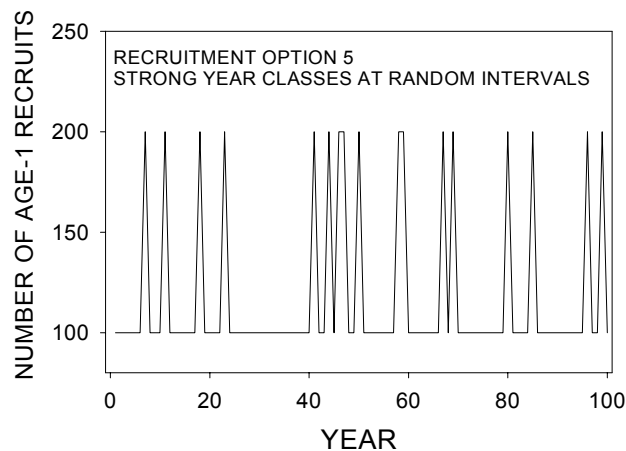
6) A **Customized recruitment** option has recently been added to the 1.1 version of FAST. This option allows the user to determine the exact recruitment pattern to be used in the simulation modeling. This is accomplished by providing the analyst with a spreadsheet into which the initial number of recruits can be entered for each year of a simulation run. Similar to other spreadsheets used in FAST, the first row is reserved for the appropriate column headers.

If an analyst has long-term recruitment data available, then this option allows the user to model under the same annual recruitment pattern that was observed from the empirical data.. In the form image depicted above, the recruitment pattern from the Weiss Lake crappie population (see table 5-1) was entered into the spreadsheet. For this example the annual age-1 CPE from Weiss Lake has been multiplied by 10 to obtain the numbers presented above. In this case, 10 years of recruitment data were available, therefore, the simulation could be run for ten years or the recruitment sequence could be copied down if the analyst preferred to model over a longer time period.

Interpretation of the FAST output for temporal patterns of recruitment

One of the output variables that may be of interest to the analyst using the six variable recruitment options is the predicted abundances of age-1 fish for all the simulation years. Examination of the temporal pattern of recruitment with the **Fixed** option will be of little interest because the number of age-1 recruits will be the same each year. After data have been entered into one of the other four recruitment options, and all other data in the main window have been

entered including the number of simulation years (**Num Years**), load the data by clicking on **L** button in the upper left tool bar, then run the analysis by clicking on **R**. An hour glass will appear until the computations are completed. Click on **View Output** then **Tabular Model Output by Year** and a window will appear where the analyst can add the desired variables to the spreadsheet and click on **Print to Spreadsheet** to view the data. At the bottom of the spreadsheet, the mean number of recruits, standard deviation, and CV are provided. A plot of the predicted number of age-1 recruits over the number of simulated years can be viewed by clicking on **View Output**, **Graphical Model Output by Year** then choosing **Year** as the independent variable and **Number of Age-1 Fish** as the dependent variable. Click on **Plot the Data** and a time-series line is presented.

6. MODELING POPULATIONS AND FISHERIES: BRINGING GROWTH, MORTALITY, AND RECRUITMENT TOGETHER

<u>Background</u>

To simulate changes in fish populations, growth, rates of fishing and natural mortality, and recruitment levels are integrated to predict the response of the population. In FAST, an analyst can use the **Yield-Per-Recruit Model** to compute thousands of simulations by varying exploitation, natural mortality rates, and length limits to explore effects on the population and fishery. The **Dynamic Pool Model** allows the analyst to simulate the effects of variable recruitment to predict population and fishery characteristics for fixed rates of exploitation and natural mortality. The **Dynamic Pool Model** also allows the analyst to alter exploitation rates during the life of a cohort to account for size selective angler harvest.

The number of fish in a cohort declines exponentially over time or age (Chapter 4; Figure 6-1). From hatching to recruitment to a minimum length (entrance into the fishery), only the force of natural mortality removes individuals from the cohort. After recruiting to the fishery, fish are removed from the cohort by fishing and natural mortality and eventually, no fish are left in the cohort. Individual weights of fish typically show a sigmoid growth response as age increases reaching an asymptote at maximum age (Figure 6-1).

The biomass of a cohort of fish typically displays a dome-shaped relation over the life time of that cohort (Figure 6-2). Growth in length and weight are rapid early in life and the biomass of an unfished cohort increases even though individuals are lost in the population due to natural mortality. The time corresponding to the peak of the dome is defined as the "critical age" which also confers a "critical length". At the peak of this dome, the population growth potential equals the removal rate due to natural mortality. Although the fish reach maximum weight at older ages, the force of natural mortality and reduction in abundance results in a decline in cohort biomass. Eventually the cohort becomes extinct as maximum age is obtained.

When exploitation of a fish population occurs, overall biomass accumulation will be reduced compared to an unfished population, unless density-dependent mechanisms compensate for part
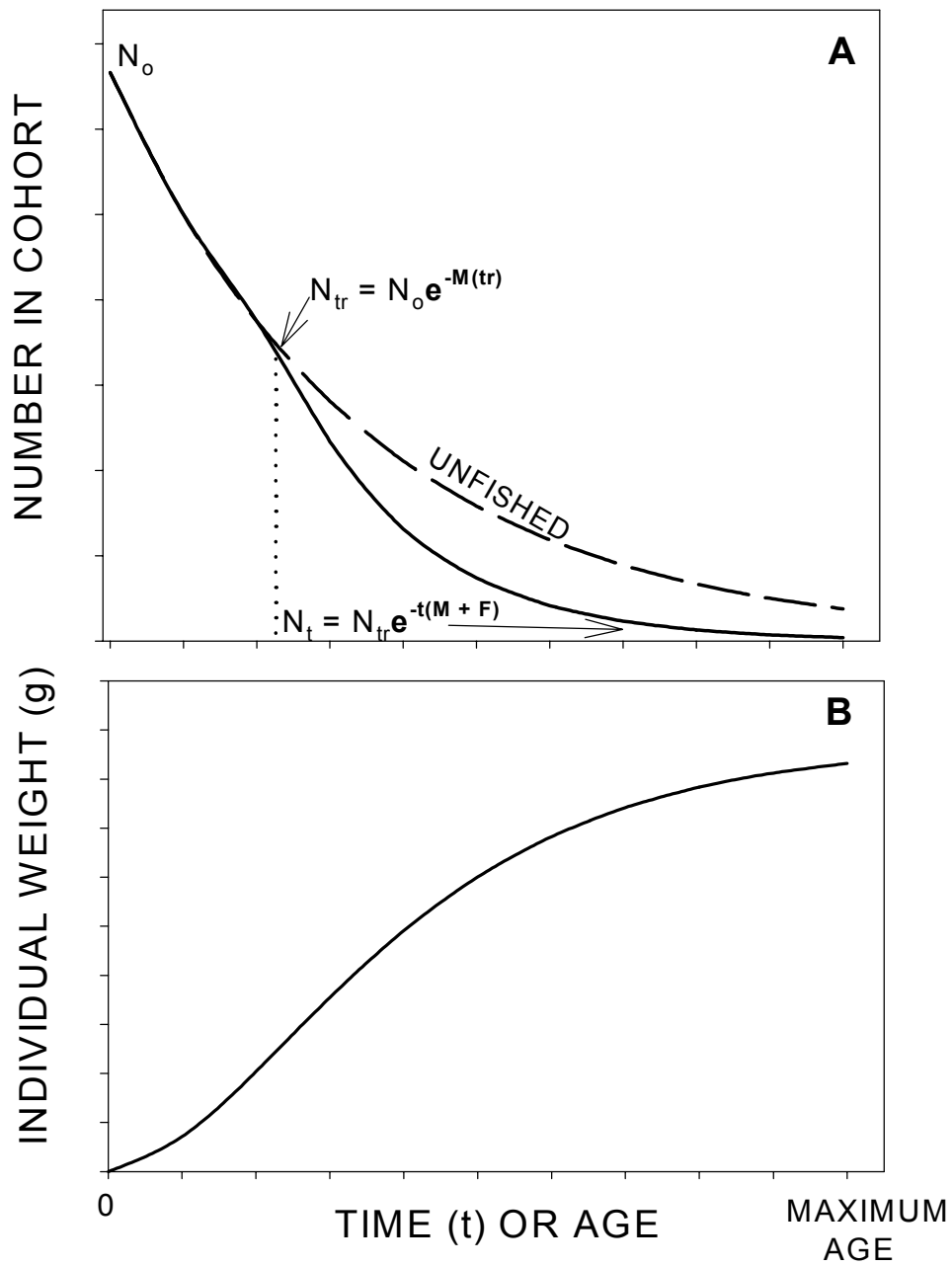
Figure 6-1. (A) Change in cohort number over time or age due to fishing mortality (solid line) compared no exploitation (unfished; dashed line). (B) Change in individual weight of of fish over time or age.
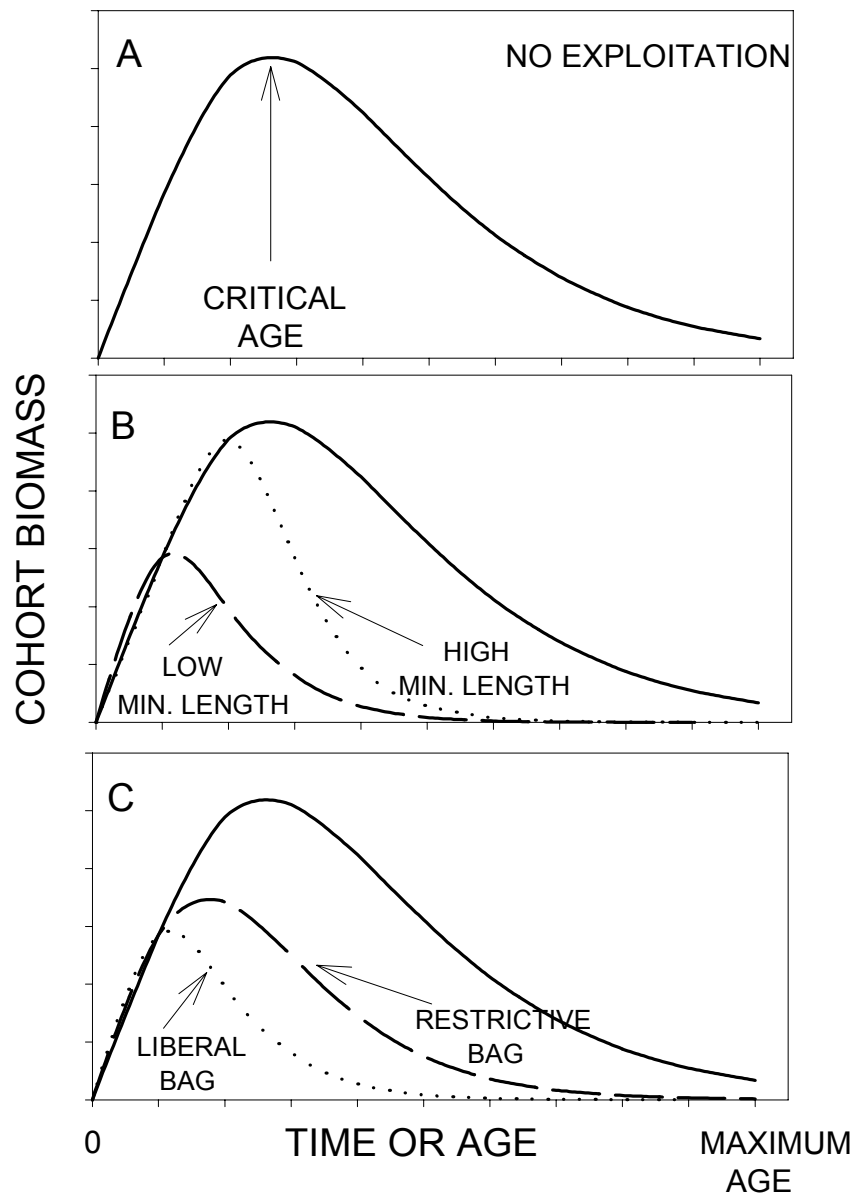
Figure 6-2. (A) Changes in cohort biomass over time in a unexploited fish population. (B) Changes in cohort biomass over time with a low minimum length (dashed line), high minimum length (dotted line) compared to no exploitation (solid line). (C) Changes in cohort biomass over time with a liberal bag (dashed line), restrictive bag (dotted line) compared to no exploitation (solid line).

of this loss. Since time to recruitment varies with different minimum length limits, moderate to heavy exploitation can drastically effect cohort biomass production. Low minimum lengths (i.e. early time of recruitment to the fishery) remove fish from the population before critical length is achieved, while higher length limits delay removal of individuals and maintain higher biomass in the population than with lower length limits (Figure 6-2). In recreational fisheries where a trophy fishery is a priority and yield is not a management goal, a minimum length equal to the critical length or longer could be selected. In a commercial fishery, where maximum yield is a desired goal, length limits should be set near the critical length and the population exploited at a high rate. In a light to moderately exploited recreational or commercial fishery, a minimum length can be set below critical length with angler expectations that harvested fish may be smaller and maximum yield will not be achieved (Figure 6-2).

Fisheries can also be regulated by adjusting exploitation. This can be accomplished with creel limits, closed seasons, and/or areas closed to fishing. Harvest can also be controlled in both recreational and commercial fisheries by regulating gear type and effort. For example, in a recreational fishery, live bait, and barb or treble hooks (induce greater hooking mortality) can be prohibited. In commercial fisheries, use of certain gear can be prohibited, or the number of traps or nets fished restricted. Restricting exploitation can either reduce or increase yield, but will maintain greater cohort biomass in the population (Figure 6-2). For a fixed time of recruitment into the fishery, liberal bag or harvest regulations will increase yield, decrease the size of fish caught, and reduce total cohort biomass production (Figure 6-2).

These concepts of minimum length limits and adjusting exploitation rates are broad generalities that will vary among populations, and will be dependent upon natural mortality, growth, recruitment, and longevity. In addition, management goals will vary, and anglers can be offered different types of opportunities (i.e. trophy versus high yield fisheries). Simulation modeling allows the analyst to explore a host of options to meet a range of management objectives.

The use of the Beverton-Holt equilibrium yield model in FAST

FAST computes yield (Y, in weight) with the Jones (1957) modification of the Beverton-Holt

6-4

equilibrium yield equation found in Ricker (1975, see equation 10.22). We have rearranged this equation to:

$$Y = \frac{F*N_t*e^{(z*r)}*W_4}{K} [\beta(X,P,Q)] - [\beta(X_1,P,Q)] \qquad 6:1$$

where:

F = instantaneous rate of fishing mortality (Chapter 4);

N_t = the number of recruits entering the fishery at some minimum length at time (t);

Z = instantaneous rate of total mortality (Chapter 4);

r = time in years to recruit to the fishery (t_r - t_o);

W_4 = maximum theoretical weight derived from predicting this weight using L_4 and the weight-to-length regression equation (Chapter 3);

K = is the growth coefficient in the von Bertalanffy growth equation (Chapter 3);

β = incomplete Beta function;

$X = e^{-Kr}$;

$X_1 = e^{-k(Maxage - to)}$ and Maxage is the maximum age of the population;

$P = Z/K$; and

Q = slope of the weight-length relation + 1.

FAST computes β, which adjusts the yield for the weight-length relation, by using a series of commercially obtained mathematical algorithms, including the gamma function and the beta distribution.

Equation 6:1, which is computationally equivalent to Ricker's equation 10.22, computes yield and associated statistics for steady-state conditions where recruitment, conditional natural mortality, and conditional fishing mortality are constant for each simulation under the **Yield-Per-Recruit-Model**. The only variable that is manipulated is the length when fish enter the fishery and can be computed for three options including fixed minimum length, variable minimum lengths, and slot limits. The time for a fish to recruit to a minimum length limit (t_r, entrance into a fishery) was determined by inverting the von Bertalanffy growth equation (see Chapter 3):

$$t_r = \frac{\log_e(1 - TL/L_4)}{-K} + t_o$$ 6:2

where:

TL = the length of fish entering the fishery.

Thus, the number of fish entering the fishery (N_t) was computed from:

$$N_t = N_o * e^{(-M*tr)}$$ 6:3

where:

N_o = number of age-0 recruits entering the population (see Chapter 5); and

M = instantaneous rate of natural mortality (Chapter 4).

The number of fish caught and harvested (N_{har}) and the number of fish dying due to natural mortality (N_{die}) were computed from:

$$N_{har} = (N_t * F)/Z$$ 6:4

and

$$N_{die} = (N_t * M)/Z$$ 6:5

The mean weight (MWT) of harvested fish was derived from:

$$MWT = Y/N_{har}$$ 6:6

and the mean total length of harvested fish was derived from MWT using the coefficients of the weight:length regression.

For the **Yield-Per-Recruit Model**, FAST will provide all associated mortality rates, t_r, associated minimum or slot lengths, and six predicted values listed in Table 6-1. These six

predicted values can be plotted as dependent variables against other independent variables in FAST.

Table 6-1.

FAST Acronym	FAST text
N(har)	Number of Fish Harvested
N(die)	Number of Fish Dying Naturally
MWT	Mean weight (g) of Fish Harvested
MTL	Mean Total Length (mm) of Fish Harvested
Yield	Yield in Kilograms
N at ___ mm	Number in Population at ___ mm

Number of Fish Harvested is the total number of fish harvested and removed from the population for a given simulation. **Number of Fish Dying Naturally** is the total number of fish dying due to natural causes. The **Mean weight (g) of Fish Harvested** and **Mean Total Length (mm) of Fish Harvested** are computed for the fish harvested and removed from the population. The **Yield in Kilograms** is the total weight harvested for each simulation. **Number in Population at ___ mm** is the predicted number of fish present at the point in time when the cohort reaches the specified **Length of Interest**, where the analyst can choose up to three different lengths. For example, an analyst may want to predict the number of largemouth bass that reach 508 mm when 406 and 457 mm length limits are simulated for certain levels of fishing and natural mortality. Computations and output for the slot limit option are similar to those previously described. However, output variables are partitioned according to the bounds of the slot limit (below slot, within slot, above slot).

For the **Dynamic Pool Model**, the entire population is simulated over time for each age class similar to Ricker's (1975) dynamic pool model. This is accomplished by employing the same equilibrium yield equation as previously described (equation 6:1) except that all values are computed on an age-specific basis rather than over the life of the cohort. This allows parameters

such as Yield, N(har), N(die), etc., to be computed for each age in the lifespan of a particular cohort. The dynamic pool model also allows the analyst to enter age-specific natural and fishing mortality rates for three user-defined age groups. However, the value entered for the minimum length limit takes precedence over age with respect to fishing mortality when the model is run. For example, if a value of 0.25 was entered for conditional fishing mortality (**cf**) between age-0 and age-4, but the time for fish to reach the minimum length was 3.5 years, the effects of fishing mortality would not occur until that time and only natural mortality would occur between age-0 and age-3.5.

   Once the age-specific computations are computed for each cohort (number of years), FAST restructures the matrix to provide a yearly representation of the population. For example, if the analyst chose to model a population over a period of ten years, the yield computed for age-6 fish in the tenth year of the simulation would be based on the number of age-0 fish produced in the fourth year of the simulation. The same logic follows for all output parameters produced by the **Dynamic Pool Model**. Accordingly, the sum of the age-specific yields produced by the **Dynamic Pool Model** will be the same as the total yield produced by the **Yield-Per-Recruit Model**, provided the same input parameters are used. This can be seen by choosing the fixed recruitment option in the **Dynamic Pool Model** and comparing the output to the **Yield-Per-Recruit Model**.

Output by Year

   For the total number of years simulated, FAST provides a spreadsheet that presents these predicted parameters for each year (Table 6-2). These variables can be plotted as dependent variables against year and viewed in FAST. When a plot is created from the **View Output** and **Graphical Model Output by Year** options and a dependent variable is chosen from the list, the analyst can place a mean reference line by clicking on **View,** then **Mean Reference Line**. This line represents the mean value of the dependent variable over time once the population has fully entered the fishery. The mean value corresponds to the mean value computed in the output provided in the **Tabular Model Output by Year spreadsheet**.

Table 6-2.

FAST output variables by year

PSD
RSD-P
RSD-M
RSD-T
Total Number of Fish in Population
Total Biomass (kg) of Fish in Population
Total Fish Harvested from Population
Total Yield (kg)
Number Age-1 Fish
Number at Stock Length
Number at Quality Length
Number at Preferred Length
Number at Memorable Length
Number at Trophy Length
Total Number Age-_ and Older
Total Number Harvested Age-_ and Older
Total Biomass Age-_ and Older
Total Yield Age-_ and Older

The first four output variables listed in Table 6-2 are size structure indices. Size structure indices and length categories follow Neumann and Anderson (1996) and species can be selected from the **Choose Species from list** window. **PSD** is proportional stock density, and **RSD** is relative stock density for preferred (**P**), memorable (**M**), and trophy (**T**) length groups. These length structure indices are computed by FAST by first calculating the number of fish that are present in each length category each year of the simulation. This is accomplished by determining when in time fish reach each length category (based on the parameters of the von Bertalanffy growth curve) and computing the appropriate numbers based on the abundance of fish in the age group immediately previous to the given length category. For example, if it takes fish 1.3 years to reach stock length, then the number of stock length fish used in the computation of the size structure indices for a given simulation year would be based on the abundance of age-1 fish during that year. Again, the same logic applies to all other length categories. FAST then computes the number in each length category and the appropriate size structure indices by using these static values.

In some cases, the parameters of the von Bertalanffy growth curve for a population will result in a situation where fish reach stock-length in less than one year. When this occurs, stock density indices will be highly dependent on the initial number of fish in the population (N_o) and the conditional natural mortality rate (**cm**) between age-0 and age-1. For example, if a population in which fish reached stock-length in less than one year was modeled with N_o fixed at 1000 for the initial number of recruits and cm between age-0 and age-1 set at 0.90, the number of fish at age-1 would be 100 and the number of fish at stock-length would be a value greater than 100. If growth is rapid during the first year of life, then higher abundance of stock-length fish would be expected in the population after holding all other functions constant. If, on the other hand, the same population was modeled with N_o fixed at 100 and cm between age-0 and age-1 set at 0.00, the number of fish at age-1 would still be 100, however, the number of fish at stock-length also would be 100, which is not correct if fish obtain stock-length before age-1. In both cases, the number of fish reaching the other length categories (quality, preferred, etc.) would be the same, as would other model output such as yield, number harvested, mean weight, etc., but the stock density indices would be different because the denominators used to compute the indices would be different. Therefore, these indices may be slightly biased and results should be interpreted with caution. Any bias will be reduced the closer the time of recruitment to stock-length is to the value of one. If this situation should arise, a message box will appear stating our recommendation that we provided above when the parameters are loaded before running the dynamic pool model.

The **Total Number of Fish in Population** is the sum of all fish from age-1 to maximum age. **Total Biomass (kg) of Fish Population** is computed by multiplying the number-at-age by mean weight-at-age. **Total Fish Harvested from Population** and **Total Yield (kg)** are the sum of the respective age groups where exploitation takes place. **The Number of Age-1 Fish** allows the analyst to examine the recruitment variability in the population when a variable recruitment option is chosen.

The last four variables listed in Table 6-2 provide the **Total Number in the Population**, **Total Number Harvested**, **Total Biomass**, and **Total Yield** for all age-classes equal to and older than a specified Age-of-Interest. The **Age-of-Interest** is by default set at age-1, but can be

set to any age between age-1 and the **Maximum Age** of the population being modeled. These four variables can be useful when evaluating changes in length limit regulations. For example, the analyst might be interested in examining the predicted change in yield of age-4 and older fish that would result from an increase in the minimum length limit.

Output by Age

FAST can provide the analyst with a spreadsheet that presents output data for each year and age class over which a simulation is conducted. Thus, for a population with a maximum age of 10 years simulated over a 25-year period, 250 lines of observations will be computed. Nine variables listed can be placed in a spreadsheet for each year and age of a cohort (Table 6-3).

Table 6-3.

FAST output variables by year and age	Description
Length	Mean length-at-age (mm)
Weight	Mean weight-at-age (g)
N-Start	Number of fish in cohort at the start of age i
Exploitation (u)	Exploitation rate of cohort at age i
Expectation of Natural Death (v)	Natural death rate of cohort at age i
Survival (S)	Survival rate ($u + v$) of cohort at age i
Biomass (kg)	Biomass of the cohort at age i
N-harv	Number of fish harvested from the cohort at age i
Yield (kg)	Yield in weight from the cohort at age i

Bivariate plots of these output predicted values can be plotted against age by selecting the **Graphical Model Output by Age** option from the **View Output** menu. For this window, the analyst has the choice to **Select year to plot age-specific output**. A year should be selected equal to or greater than the maximum age so that all year classes have recruited into the fishery. If a variable recruitment option is chosen, then graphical output will vary each year among the total years the simulation was conducted.

Summary

   This chapter has provided a brief overview of modeling with FAST. The following four

chapters provide more detailed examples of modeling and interpretation of results. By working

through the examples in the following chapters, the analyst should become familiar with all the

functions provided by FAST. The examples were developed using data from actual fish

populations and illustrate the utility of modeling as a useful tool in the analysis and management

of fish populations. While working through the examples, if questions arise regarding the

formulae and methods used to derive model parameters or how the model computes output,

please refer to Chapters 2 - 6 of this manual.

7. SIMULATED EFFECTS OF MINIMUM LENGTH LIMITS ON THE SAUGER FISHERY IN THE TENNESSEE RIVER

<u>Background</u>

We present an example of using FAST to evaluate the potential effects of a length limit on the sauger fishery of the Tennessee River in Alabama. The data and analyses used in this example are from Maceina et al. (1998b). This paper can be examined by the user from the HTML file included with this software, and opened with the Acrobat 4.0 reader. This example primarily shows the utility of modeling and selecting a length limit when estimates of exploitation were highly uncertain. Maceina et al. (1998b) reported that estimates of exploitation rates ranged from 30 to 90% due to disparities in data collected for angler non-reporting. However, based on the age frequency distribution, exploitation likely ranged from 40 to 60% in 1993-95, the bag limit was 15 fish per day, and no length limit existed. Based on angler returns of reward tags, the minimum length sauger retained by anglers was about 254 mm. Maceina et al. (1998b) used MOCPOP (Beamdesfer 1991) to simulate harvest with a 254 and 356 mm TL limit to predict fishery responses. A management goal was to increase the yield to anglers and prevent growth over fishing. In this example, we duplicate the results presented in Maceina et al. (1998b) with FAST. Similar results were produced by both software programs.

<u>Modeling the sauger population</u>

Open the **Tenn_River_Sauger.par** sample file from the **Yield-Per-Recruit Model** window. Within the **Model Parameters** frame, **Min TL (mm)** and N_o of 254 and 100 appear in the boxes. The regression coefficients for the weight:length and the von Bertalanffy growth equations and a **Max age** (maximum age) of 10 years have been entered. These values are identical to those in Maceina et al. (1998). Weight infinity [**Winf (g)**] was previously computed and saved by FAST for this file when the weight:length and von Bertalanffy coefficients are entered and Load (**L)** is clicked. In the modeling options frame, choose **Model by Varying Minimum Length** and notice within the **Minimum Total Length (mm)** frame, **start** is 254, **end** is 356, and **step by** is

102. This indicates the lowest minimum length to be evaluated is 254 mm, the highest is 356, and this is a difference of 102 mm. Alternatively, the analyst could choose a number of incremental minimum lengths. For example by entering 250 mm for **start,** 350 mm for **end**, and 25 mm for **step by**. Minimum length limits of 250, 275, 300, 325, and 350 mm would be simulated   .

Within the **cm - Conditional Natural Mortality** frame, rates of 0.25, 0.40, and 0.15 are given for **start**, **end**, and **step by**, respectively, similar to those used by Maceina et al. (1998a). Within the **cf - Conditional Fishing Mortality** frame, rates **start** at 0.2, **end** at 0.8, **step by** 0.1, which approximate the values used by Maceina et al. (1998a). Click **L** to load the information, and a value of 28 appears in the upper left window that informs the analyst that 28 lines of data will be produced or 28 simulations conducted using the input data (7 cf's x 2 cm's x 2 length limits). Click **R** to run, **View Output**, and select **Tabular Model Output** to examine the output in a spreadsheet. A total of 16 different variables including the minimum lengths, cm's, cf's, time of recruitment to the minimum length, all mortality rates (AM, S, F, M, Z, u, and v), harvest number, number dying naturally, average length and weight of harvested fish, and yield can be viewed by clicking **Add** and **Print to Spreadsheet**. The data can be save as a **vts** file by

activating the spreadsheet and choosing **Write**. The spreadsheet in FAST has some editing capabilities comparable to Microsoft Excel. Because FAST **vts** data files cannot be imported directly into Excel and other graphic packages, the analyst should choose to save the data as an Excel or text formatted file if this type of compatibility is required. See Chapter 11 for a more detailed description of FAST's spreadsheet module.

When conducting simulation modeling, the analyst will find that the vast amount of output data provided may be difficult to interpret in tabular form. Graphic presentation greatly assists in interpretation and evaluation.

To graphically view some of the more important results, change the **cm - Conditional Natural Mortality**, **end** from 0.40 to 0.25. Thus, only one rate of conditional natural mortality will be simulated. Click **L**, 14 simulations will be conducted, and click **R**. From the **View Output** menu, clicking on **Graphical Model Output** reveals a window that displays a host of independent variables that can be plotted against the dependent variables listed in Table 6-1. Typically the best independent variable to choose is **Rate of Exploitation (u)**. For this example, we choose to plot exploitation against yield, number harvested, and mean weight of harvested fish by each minimum length by clicking **View Plot By TL**, then clicking **Plot the Data**. Plots similar to those below should be generated.
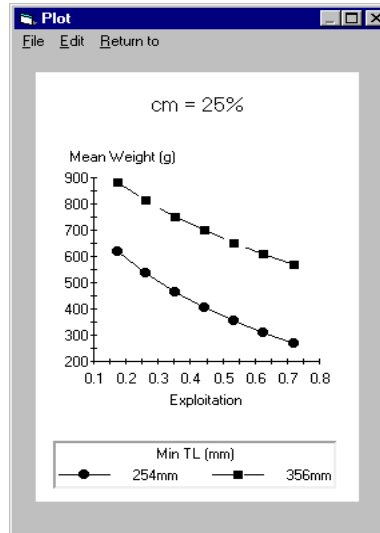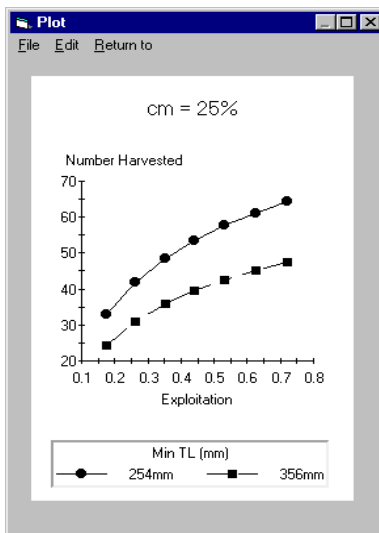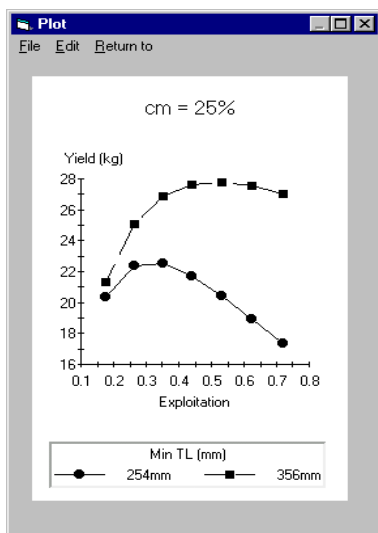
Conduct the same analysis again, but change conditional natural mortality to 0.40 in the **start** and **end** boxes. In this population, estimates of natural mortality were also uncertain and as natural mortality increases, the utility of higher length and lower bag limits to achieve maximum yield is diminished. Yield, number harvested, and mean weight of harvested fish decline because greater numbers of fish are being removed from the fishery at the higher conditional natural mortality rate of 40%.
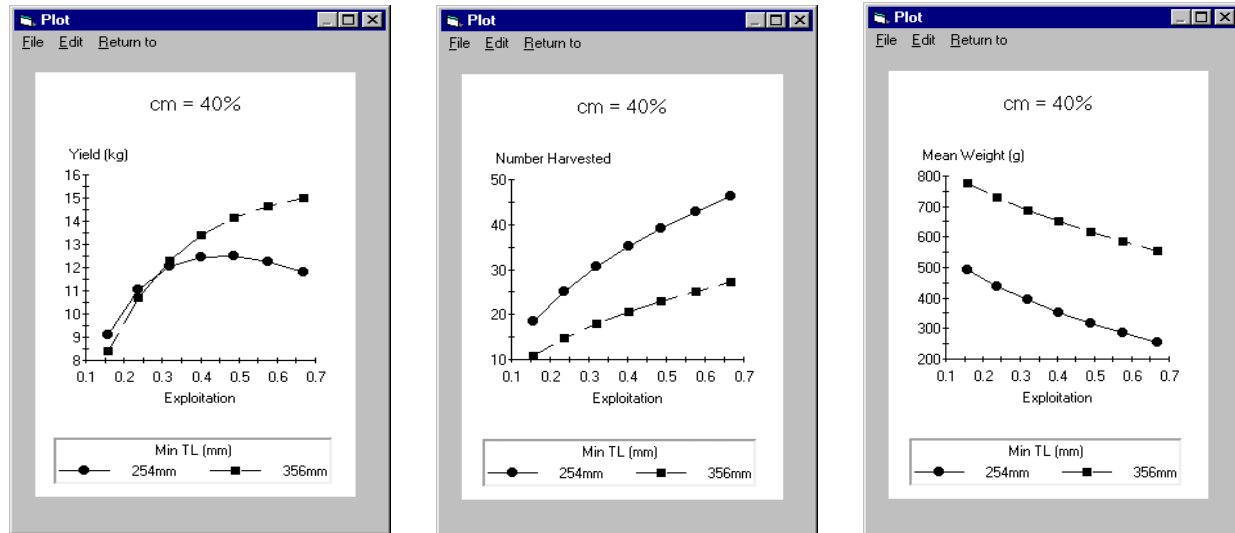
At a conditional natural mortality of 25%, growth overfishing was evident when exploitation exceeded 40% with the 254 mm length limit, but this was not observed with the 356 mm length limit. Growth overfishing occurs when the population is harvested at such a high rate and at a early age of recruitment to the fishery that the full growth potential of the population has been severely reduced and maximum yield cannot be achieved. In any exploited fishery, growth overfishing should be avoided. Higher yields were predicted with the 356 mm length limit when exploitation was greater than 20%, but the number of fish that could legally be harvested was reduced by 26%. With the higher minimum length limit and exploitation between 40 and 60%, harvested sauger average about 0.6 to 0.7 kg compared to about 0.3 to 0.4 kg at the lower length limit. Thus, a trade-off existed, where a 356 mm length limit would increase yield and size of fish kept by anglers, but fewer fish could be harvested compared to the 254 mm length limit.

At a conditional natural mortality rate of 40%, the same trends were evident, but differences

in yield were not as great. Yields were nearly identical when exploitation was less than 40%, but higher yields were predicted with the higher length limit at greater exploitation rates. Thus, recommending a 356 mm minimum length limit was a very safe decision even though uncertainty existed in estimates of fishing and natural mortalities.

In FAST, we have adapted Beverton and Holt's (1957) original application of determining maximum yield from exploitation and time of recruitment into the fishery by creating yield isopleths. To create a yield isopleth, numerous simulations are conducted with small increments of conditional fishing mortality and length limits between the minimum and maximum values for these variables. For this example, enter 0 for **start**, 0.8 for **end**, and 0.01 for **step by** in the **cf - Conditional Fishing Mortality** frame. For the **cm - Conditional Natural Mortality** frame enter 0.25 for s**tart**, 0.40 for **end**, and 0.15 for **step by**. For **Minimum Total length (mm)**, enter **start** at 200, **end** at 450 , and **step by** 5. Click **L**, FAST indicates that 8,262 simulations will be computed, then click **R** to run. A high number of simulations are needed to create smooth contours for isopleth plots and typically will only take your PC a few seconds to run. From the **View Output** menu, click **Yield Contour Plot**, and a graph will appear with the minimum TL on the y-axis, exploitation on the x-axis, and isopleth lines labeled for various predicted yields. Color plots are easier to interpret than black and white. By default, the lower conditional natural mortality rate will appear. At the bottom of the graph **choose level of cm** to change the natural mortality rate.
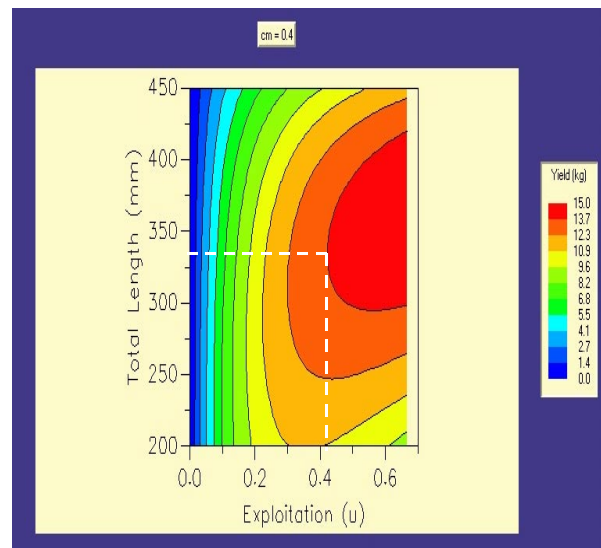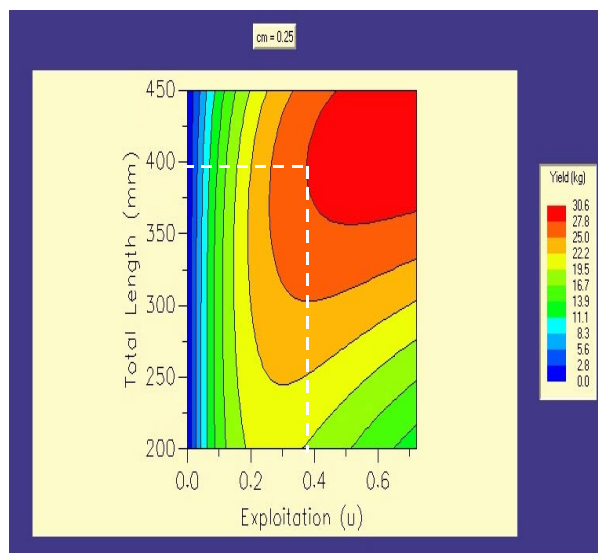
By drawing a vertical line that is tangent to the left side of the maximum yield isopleth line of 30.6 kg, and extending this line to the x-axis indicates a minimum exploitation rate of about 38%. At the point of this tangent, extending a line parallel to the x-axis intercepts the y-axis at about 400 mm. In a commercial fishery where the goal is maximum yield with minimum fishing effort, a 400 mm length limit could be established and fishing effort adjusted to achieve a 38% exploitation rate. Commercial fisheries attempt to not only maximize yield, but also profit, and to minimize costs associated with exploitation. Thus, by minimizing fishing effort and maximizing yield, greater profit can be achieved. In recreational fisheries where harvest is a priority, these plots allow the analyst to examine the potential range of conditions currently in the fishery. If adequate catch rates and moderate size fish are also sought, then a minimum length and exploitation rate in the region below and to the left of the tangent point for maximum yield could be considered.

At a conditional natural mortality of 40%, a tangent to the left side of the isopleth line for maximum yield extending to the x and y-axes intersects exploitation at 42% and a minimum length of about 330 mm. Again, uncertainty in the estimation of natural mortality exists, and the 356 mm minimum length limit appears to be a good decision given the goals of the fishery. Finally, by clicking on the **View Output** menu and **Catch Contour Plot,** isopleth lines of number caught (harvest) by exploitation rate and minimum length is provided.
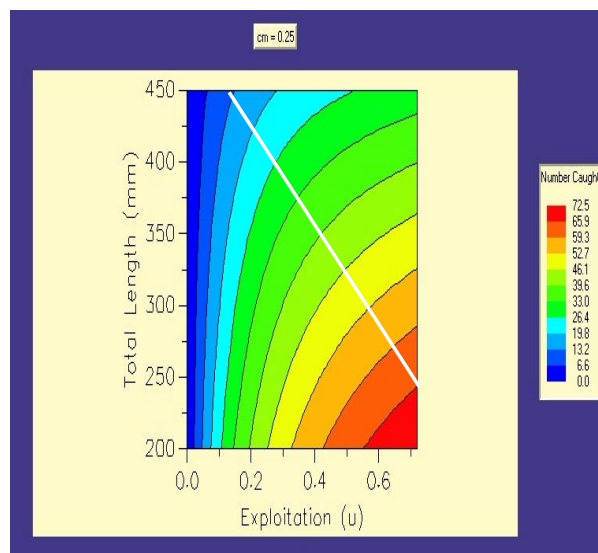
Obviously, as the minimum length decreases and exploitation increases, the number caught will increase. One utility of the interpretation of this plot would be to draw points that are tangent at the points of inflections for each isopleth line using a 45° angle. For a given minimum length, higher exploitation rates to the right of the tangent point predict higher catches, but these relations start to flatten. Thus, progressively higher exploitation does not confer a proportionally greater catch. If this occurs, catch in the fishery may increase, but catch-per-hour and size of fish harvested will decrease. Thus, to increase benefits to the fishery for example with a 356 mm minimum length limit, exploitation could be adjusted about 40%. This level of exploitation would achieve the goal of maximum yield and provide for an improved sport fishery. Greater exploitation rates would lead to smaller fish harvested by anglers and lower catch-per-effort.

Management recommendations and actions

In October 1995, the Alabama Department of Conservation and Natural Resources imposed a 356 mm length limit on sauger and reduced the daily bag from 15 to 10 with three fish under 356 mm allowed per angler. The impact of a bag reduction is more difficult to predict because all anglers will not catch a limit of fish and the number of fish less than 356 kept by anglers is uncertain. However, a reduction in exploitation may occur and this was encompassed in the range of harvest rates that we simulated. Although exploitation and to some extent natural mortality rates were uncertain, imposing this 356 mm length limit on the population was a safe management decision with the goal of increasing yield in this fishery.

8. THE EFFECTS OF VARIABLE RECRUITMENT ON THE EVALUATION OF A 254 mm LENGTH LIMIT FOR CRAPPIE IN WEISS LAKE

<u>Background</u>

   Maceina et al. (1998a) used a Beverton-Holt equilibrium yield model (SAS 1988, equation 10:23 in Ricker 1975) to evaluate four minimum length limits (203, 229, 254, and 279) on black crappie and white crappie yield and harvest in Weiss Lake, Alabama. The user can access this paper as a HTML file contained on the FAST CD-Rom. Two years after a 254 mm minimum length limit was imposed in 1990, angler catch-per-effort for harvestable size fish doubled and catch rates for all sizes of crappie were 2-4 times higher when compared to the time period when no minimum length existed (Figure 8-1). However, modeling results predicted lower angler catches (harvest) of crappie after the length limit went into effect (Maceina et al. 1998a). Simulation modeling only showed a modest increase in yield with the 254 mm length limit compared to 203 mm (minimum size retained by anglers). Examination of creel data indicated tremendous success of the higher minimum length, but these data were confounded by highly variable recruitment. Prior to 1990 and the establishment of the 254 mm minimum length, crappie reproductive success was very poor (Figure 8-2). However, a strong year class was produced in 1990, and moderate reproductive success occurred in 1993 and 1994 which masked the true effects of the new minimum length on the population and fishery (Maceina et al. 1998a). In this example, we explore the effects of reduced and variable recruitment of crappie on this fishery in Weiss Lake.
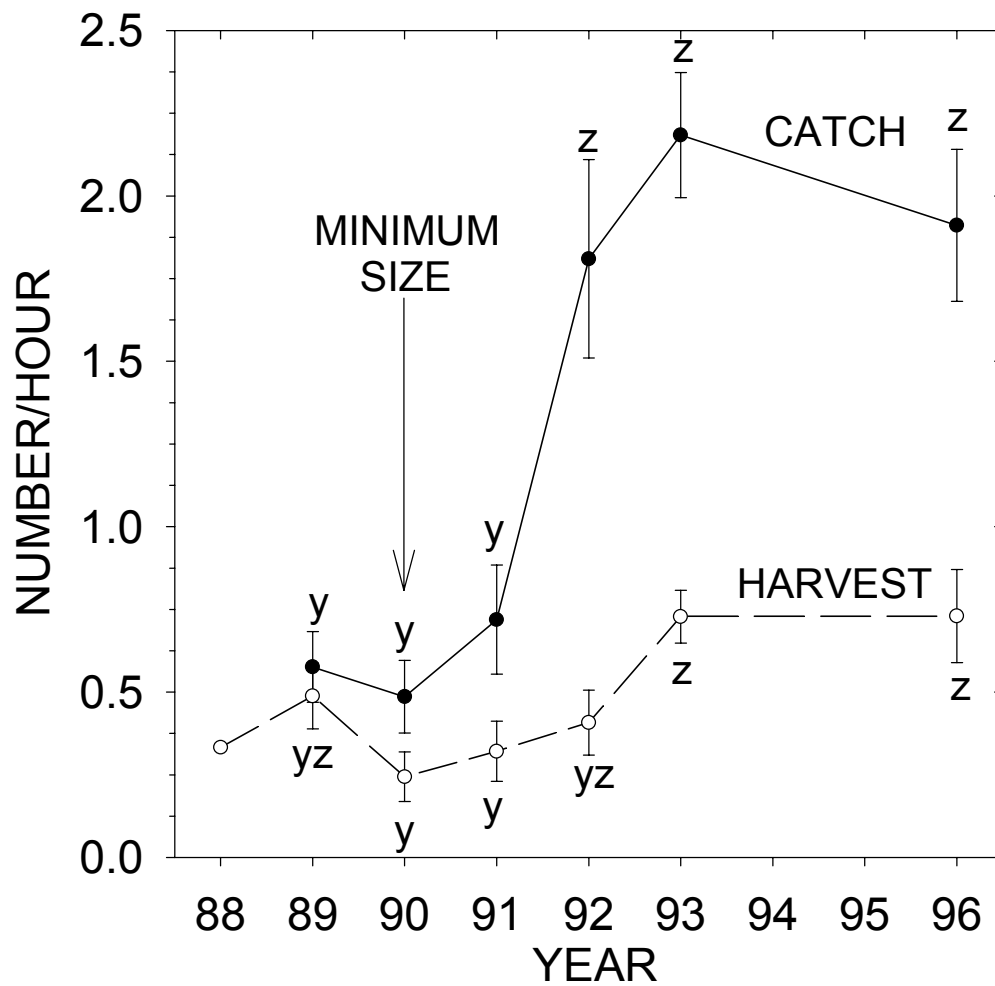
Figure 8-1. Angler catch and harvest rates of crappie from 1 March to 31 May in Weiss Lake, Alabama, 1989-1996. Annual ratio-of-mean estimates followed by the same letter for each catch and harvest were not different (P > 0.05). Raw data were not available from 1988 and not included in the statistical analysis. (Figure is from Maceina et al. (1998a).
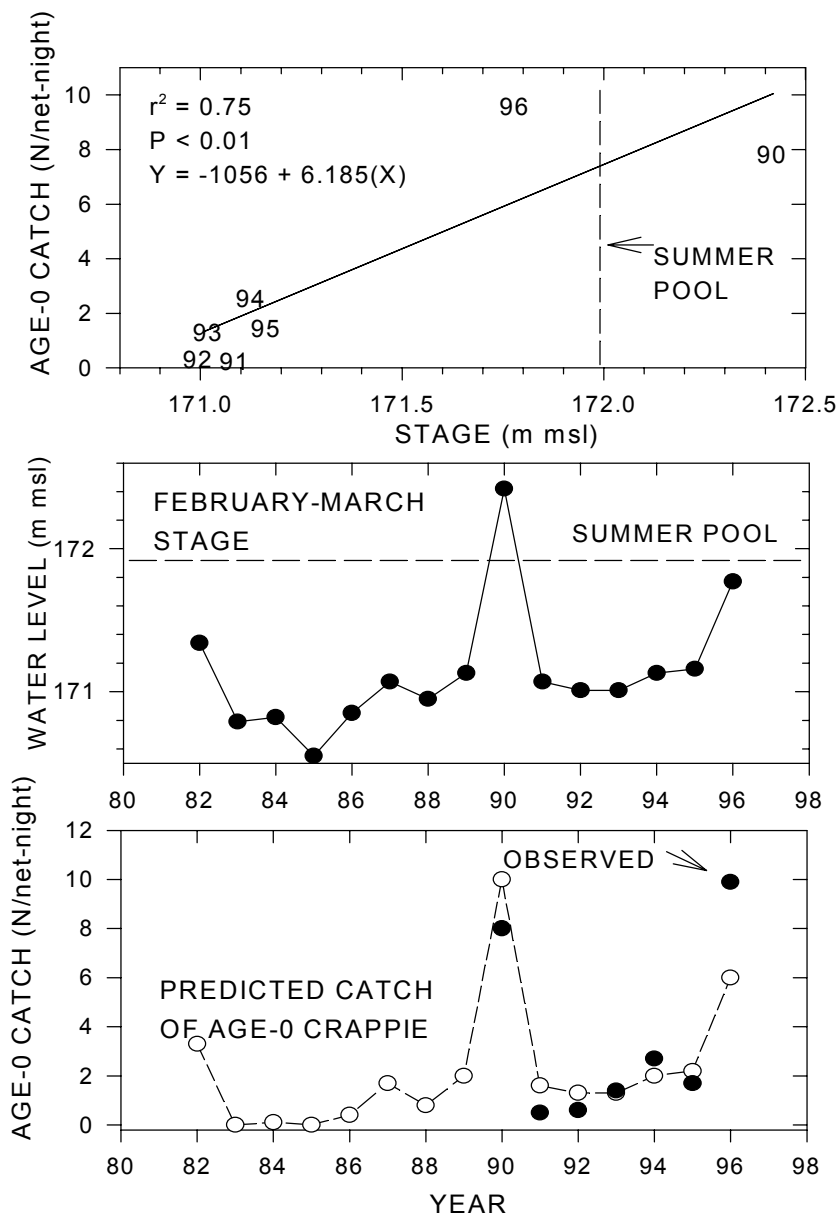
Figure 8-2. The relation between average stage in February-March and catch rates of age-0 crappie in Weiss Lake, Alabama. Numeric values represent year classes (top). Average stage in February-March from 1982 to 1996 (middle). Predicted catch of age-0 crappie (from regression in top panel) from 1982 to 1996 compared with observed catches from 1990 to 1996 (bottom). Figure is from Maceina et al. (1998a).

Modeling the crappie population

    From the samples files offered by FAST, open **Weiss_Crappie.par**, and click on **Model by
varying Minimum Length**. Identical coefficients for the weight:length and von Bertalanffy
growth equations, and similar values for conditional fishing mortality and conditional natural
mortality are shown that were presented in Maceina et al. (1998a). For **Minimum Total Length
(mm)**, four different minimum lengths (204 to 279 by 25 mm) will be simulated, similar to
lengths used by Maceina et al. (1998a). For **cm - Conditional Natural Mortality**, enter 0.25 for
start and **end**, click **L**, then **R** and 44 simulations will be computed.
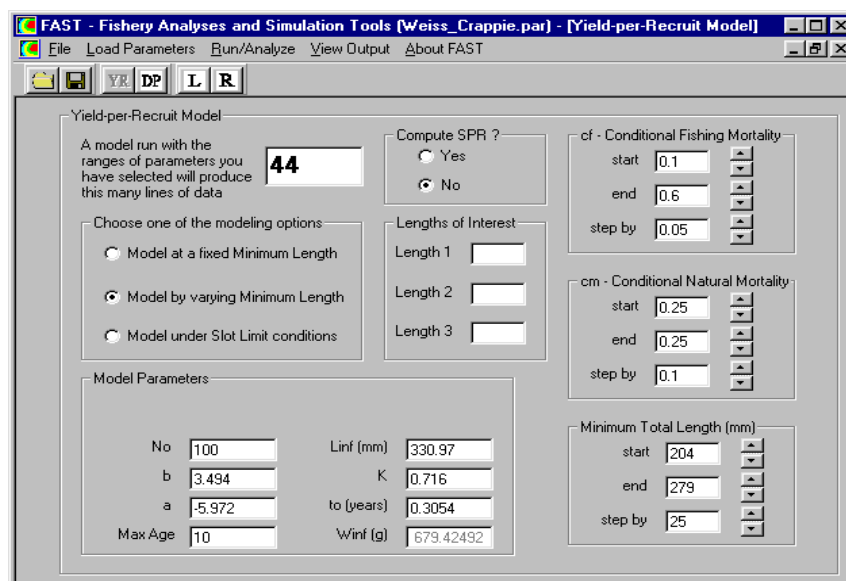
From the **View Output** menu, click **Graphical Model Output**, and **View Output by TL**. Plot
exploitation against both yield and number harvested. These graphs are nearly identical to those
presented in Figures 5 and 6 in Maceina et al. (1998b). Change conditional natural mortality to
0.35 and 0.45, run the simulations, and view the same plots. These plots also correspond to
Figures 5 and 6 in Maceina et al. (1998b). Similar to the interpretation of Maceina et al. (1998b),
the FAST plots indicate slight improvement in yield with a 254 mm minimum length limit
compared to lower length limits if conditional natural mortality is 35% or less. At progressively
higher minimum length limits, fewer crappies will be harvested, and these differences become
greater as natural mortality increases. Thus, model predictions contradict angler harvest rates
(Figure 8-1).

In FAST, we can examine the confounding effects of recruitment on model predictions and creel data. The predicted catch-per-effort of age-0 crappies in trap nets (N/net-night) from 1983 to 1989 was low due to reservoir hydrologic conditions and averaged 0.90 fish/net-night (Figure 8-2). From 1990 to 1994, crappie reproductive success improved and 2.53 age-0 fish/net-night were captured. Thus, recruitment of crappie was about 65% less from 1983 to 1989 compared to 1990 to 1994.

Differences in recruitment levels can be incorporated into FAST to predict the impact on the fishery and these results can be compared to the creel data presented in Figure (Figure 8-1). To conduct this analysis using the **Yield-Per-Recruit Model** for the **Weiss_Crappie.par** file, change N_o from **100** to **35**. This would represent a 65% decline in age-0 recruitment. Choose the **Model at fixed Minimum Length** option and change **Min TL (mm)** in the **Model Parameter** windows from **254** to **203**. Density-dependent growth compensation was not evident for crappie in Weiss Lake, but in other Alabama reservoirs there was an inverse relation between trap net catch rates at age and mean length-at-age (Ozen 1997). Thus, the coefficients for the weight:length and von Bertalanffy growth equations do not have to be altered. In addition, we made the assumption that density-dependent survival did not change.   In the **Lengths of Interest** window, enter 203 for **Length 1** and 254 for **Length 2**. This feature provides the analyst with abundance predictions for fish greater than certain lengths that may or may not reach a certain minimum or slot length.   This is of interest because these fish can be caught and released by anglers if not within a length limit, or these fish, for example, can represent abundances of memorable or trophy size fish.

Load (**L**), then run (**R**) the model, and two plots can be created; exploitation versus number at (greater than) 203 mm and exploitation versus number harvested. From the **View Output** menu, choose **Graphical Model Output**, and **View plot by cm** to plot number harvested by the different rates of natural mortality. Make sure **cm - Conditional Natural Mortality** starts, ends, and steps by 0.25, 0.45, and 0.10, respectively. In the number at 203 mm versus exploitation plot, three straight lines are shown, showing the number of fish at 203 mm in the population for the three different levels of conditional natural mortality. There is no change in number with increasing exploitation because fish have just recruited to the fishery at 203 mm. Number harvested increases with exploitation, but as expected, number harvested will decrease as conditional natural mortality increases. These plots represent conditions prior to 1990 when recruitment was low and no minimum length limit was in effect.
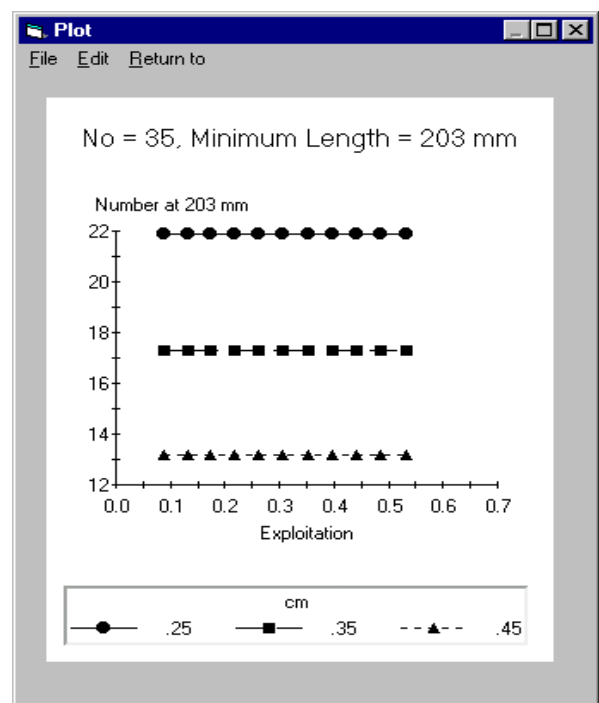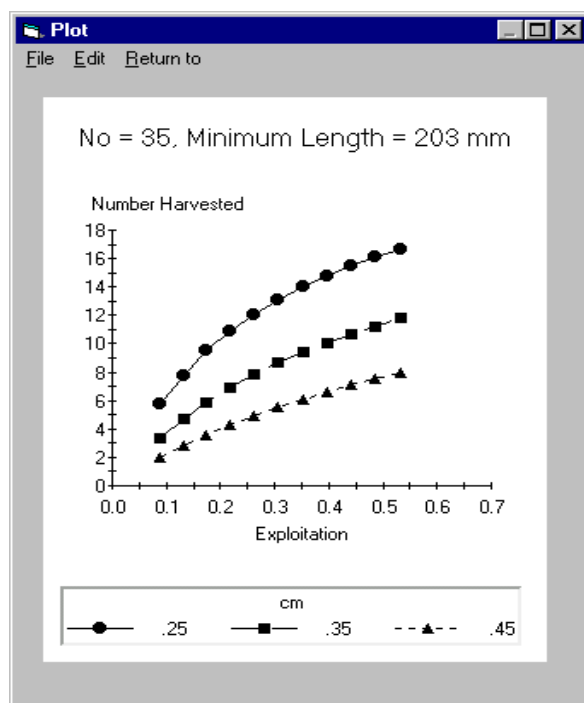
To compare these results to conditions after 1989, change N_o from **35** to **100** and **Min TL (mm)** from **203** to **254** in the **Model Parameters** window, then re-run the model. View the same plots for these simulations.
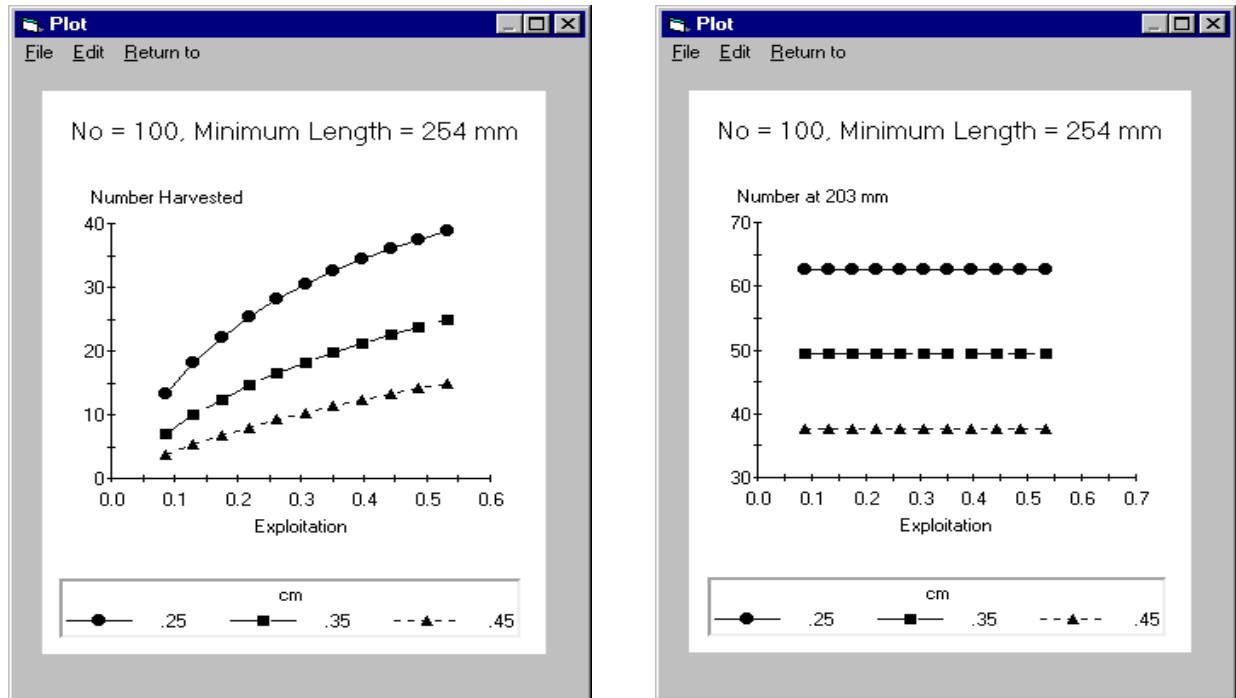
Number at 203 mm and harvest numbers for given levels of conditional natural mortality and exploitation are greater when compared to the 203 mm minimum length when recruitment was 65% less. From the data presented in these plots or from data presented in the spreadsheet, 2.9 times as many crappie greater than 203 mm were in the population after 1989 than prior to this time. If we assume angler catch is proportional to the abundance of certain size fish, this increase corresponds well to the 2-4 fold increase in angler catch rates of crappie (Figure 8-1). For all rates of fishing and natural mortality, FAST predicted harvest number was 2.3 times higher after 1989 when recruitment increased and the 254 mm length limit went into effect compared to 1983 to 1989 (203 mm length limit and lower recruitment). This prediction closely corresponded to actual angler harvest of crappie, which doubled after 1989 (Figure 8-1). Precise differences in fishery and population characteristics are best obtained by examining the spreadsheet output (Figure 8-3).

Model Output - 1

Spreadsheet Return

	A	B	C	D	E	F	G	H
1	Min TL (mm)	cm	cf	u	Nharv	Yield (kg)	N at 203 mm	N at 254 mm
2	203	0.25	0.1	0.087	5.72	2.462	21.88	16.55
3	254	0.25	0.1	0.087	4.62	2.357	21.88	17.84
4	203	0.25	0.15	0.131	7.78	3.213	21.88	15.9
5	254	0.25	0.15	0.131	6.31	3.141	21.88	17.84
6	203	0.25	0.2	0.175	9.48	3.749	21.88	15.23
7	254	0.25	0.2	0.175	7.7	3.741	21.88	17.84
8	203	0.25	0.25	0.219	10.89	4.124	21.88	14.54
9	254	0.25	0.25	0.219	8.86	4.2	21.88	17.84
10	203	0.25	0.3	0.263	12.08	4.379	21.88	13.85
11	254	0.25	0.3	0.263	9.84	4.551	21.88	17.84
12	203	0.25	0.35	0.307	13.1	4.543	21.88	13.14
13	254	0.25	0.35	0.307	10.68	4.819	21.88	17.84
14	203	0.25	0.4	0.352	13.99	4.639	21.88	12.41
15	254	0.25	0.4	0.352	11.4	5.022	21.88	17.84
16	203	0.25	0.45	0.397	14.77	4.683	21.88	11.67
17	254	0.25	0.45	0.397	12.04	5.176	21.88	17.84
18	203	0.25	0.5	0.442	15.46	4.687	21.88	10.91
19	254	0.25	0.5	0.442	12.6	5.29	21.88	17.84
20	203	0.25	0.55	0.487	16.09	4.659	21.88	10.12
21	254	0.25	0.55	0.487	13.11	5.372	21.88	17.84
22	203	0.25	0.6	0.533	16.65	4.607	21.88	9.31
23	254	0.25	0.6	0.533	13.58	5.429	21.88	17.84

Sheet1

Model Output - 2

Spreadsheet Return

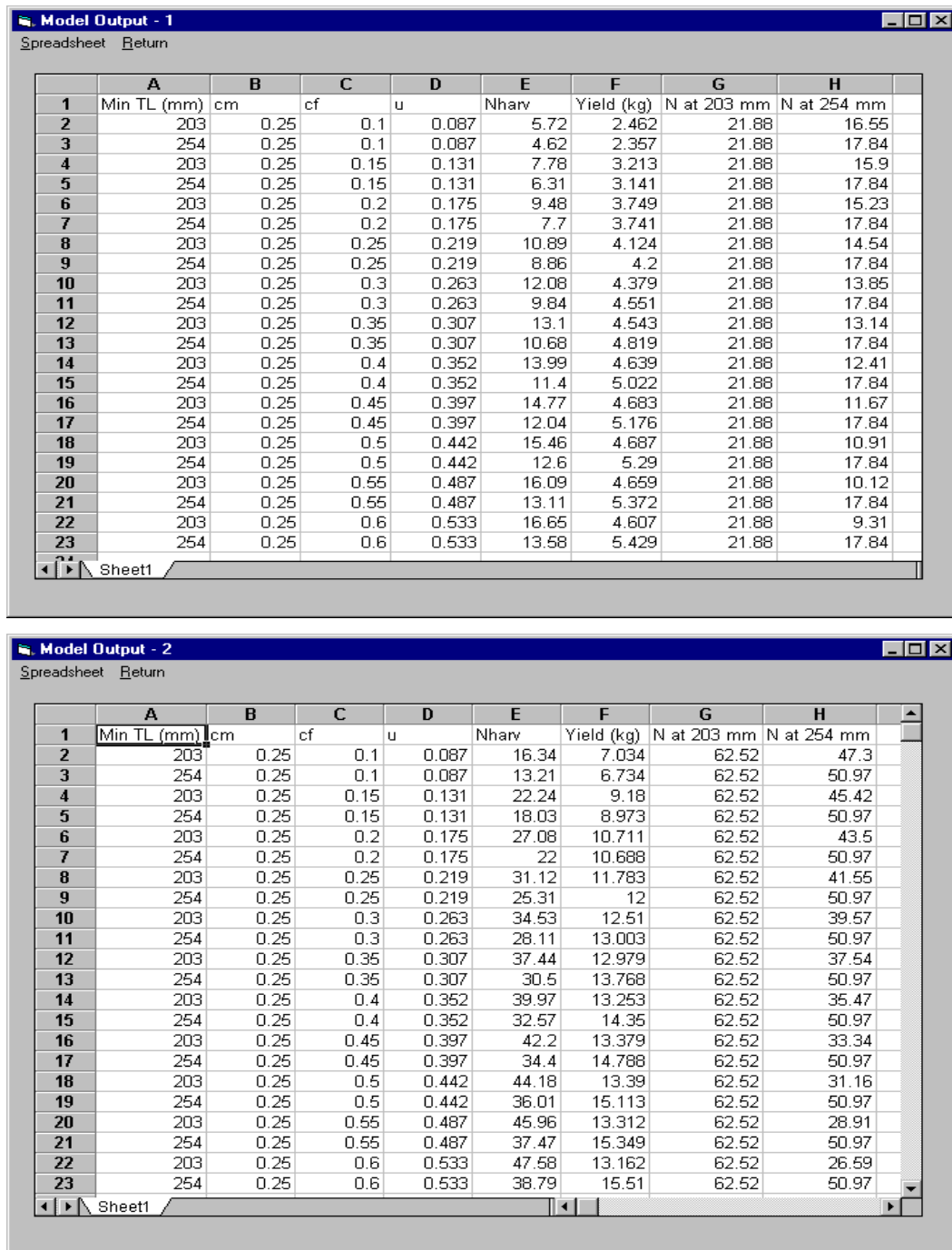|	A	B	C	D	E	F	G	H
1	Min TL (mm)	cm	cf	u	Nharv	Yield (kg)	N at 203 mm	N at 254 mm
2	203	0.25	0.1	0.087	16.34	7.034	62.52	47.3
3	254	0.25	0.1	0.087	13.21	6.734	62.52	50.97
4	203	0.25	0.15	0.131	22.24	9.18	62.52	45.42
5	254	0.25	0.15	0.131	18.03	8.973	62.52	50.97
6	203	0.25	0.2	0.175	27.08	10.711	62.52	43.5
7	254	0.25	0.2	0.175	22	10.688	62.52	50.97
8	203	0.25	0.25	0.219	31.12	11.783	62.52	41.55
9	254	0.25	0.25	0.219	25.31	12	62.52	50.97
10	203	0.25	0.3	0.263	34.53	12.51	62.52	39.57
11	254	0.25	0.3	0.263	28.11	13.003	62.52	50.97
12	203	0.25	0.35	0.307	37.44	12.979	62.52	37.54
13	254	0.25	0.35	0.307	30.5	13.768	62.52	50.97
14	203	0.25	0.4	0.352	39.97	13.253	62.52	35.47
15	254	0.25	0.4	0.352	32.57	14.35	62.52	50.97
16	203	0.25	0.45	0.397	42.2	13.379	62.52	33.34
17	254	0.25	0.45	0.397	34.4	14.788	62.52	50.97
18	203	0.25	0.5	0.442	44.18	13.39	62.52	31.16
19	254	0.25	0.5	0.442	36.01	15.113	62.52	50.97
20	203	0.25	0.55	0.487	45.96	13.312	62.52	28.91
21	254	0.25	0.55	0.487	37.47	15.349	62.52	50.97
22	203	0.25	0.6	0.533	47.58	13.162	62.52	26.59
23	254	0.25	0.6	0.533	38.79	15.51	62.52	50.97

Sheet1

Figure 8-3. FAST output spreadsheets for model simulations predicting yield, harvest number (Nharv), number at 203 mm (N at 203 mm), and number at 254 mm (N at 254 mm) for two different minimum lengths and numerous rates of conditional fishing mortality. The top spreadsheet simulated low recruitment ($N_o = 35$) conditions and the lower spreadsheet simulated high recruitment ($N_o = 100$). Conditional natural mortality was 25%.

The effects of density-dependent mortality under reduced or increased levels of recruitment as well as the effects of highly variable recruitment on the population and fishery can be assessed in FAST by using more detailed analysis that utilizes age structure information. This analysis is conducted by using the Dynamic Pool Model and is run in FAST by clicking on the **DP** button in the toolbar. Open the **Weiss_Crappie.par** sample file again, and white crappie appears by default on the species list. Although Weiss Lake contains both crappie species, length-structure categories are the same for both species. The terms in the **Model Parameters** are the same as those used in the **Yield-Per-Recruit Model** for crappie from Weiss Lake.

As in the previous example, if the analyst collected data that showed higher survival rates of young fish in the 1980's when recruitment was low, adjustment to the data in the **Variable Recruitment Options** and **Mortality Options** frames can be made. For the higher recruitment scenario, click on **Fixed** in the **Variable Recruitment Options** frame, and use the default value of 1,000 recruits. For **Mortality Options**, enter **0.9** for **cm** for age-0 to age-1 fish and enter **100** for **Num Years**. Thus, 100 fish will recruit to age-1 each year for a 100 year simulation. For fish from age 1 to age 10, a single conditional natural mortality rate and conditional fishing mortality rate are entered. Load (**L**), run (**R**) the model, and from the **View Output** menu, select

the **View Tabular Model Output by Year** spreadsheet. Add the desired variables to the spreadsheet then select **Print to Spreadsheet**. Because the maximum age of crappie has been specified as 10 years, steady-state conditions in the population will be evident from Years 11 to 100 in the output. To simulate conditions during the low recruitment period, enter **350** for **Fixed** in the **Variable Recruitment Option,** which is similar to the previous analysis, and represents a 65% reduction in age-0 recruits. If the analyst collected data and determined that the conditional rate of natural mortality between age-0 and age-1 was 80%, then **0.80** instead of **0.90** could be entered in the **cm** for this age group. Thus, 70 fish would recruit to age-1. Rerun the model again with all other terms being identical, allowing for comparisons to be made.

Finally, long-term fluctuations in population characteristics and the fishery can be assessed by the analyst based on the magnitude of random variation in recruitment. In Table 5-1, the coefficient of variation of age-0 trap net catch rates of crappie in Weiss Lake was 98%. This variation in recruitment can be modeled over time by choosing **Random (normally distributed)** from the **Variable Recruitment Option** frame and entering 980 for the **standard deviation of recruitment** box and leaving 1,000 as the default for the **Mean number of recruits**. In the **Mortality Options** frame, enter **0.9** for **cm** and leave the box for **cf** blank. Enter **0.25** and **0.40** for the **cm** and **cf** boxes, respectively, for age-1 to age-10 fish which approximates conditions in the fishery (Maceina et al. 1998b). In the **Model Parameters** frame, enter **254** for **Min TL (mm)** and **50** in the **Num Years** box to run a 50 year simulation. Load and run the model, then graphically view the yield, number harvested, and number at age-1 over the 50 year time period by choosing **Graphical Model Output by Year** from the **View Output** menu and choosing the appropriate variables to plot (Figure 8-4).

Yield and harvest number vary greatly and as expected, fluctuate by a 2-3 year lag behind the number of age-1 recruits (Figure 8-4). Based on creel data, the perceived success or failure of the 254 mm length limit by anglers will be dependent on the presence and periodicity of high or low recruitment periods. From Year 28 to 37, age-1 recruitment was above average for 8 of 10 years. From Year 30 to 39, yield and number harvested was either average or above average , and in some years these values were about twice as high as the average. Conversely, from Year 38 to 42, recruitment was generally below average and this corresponded to lower yield and catch
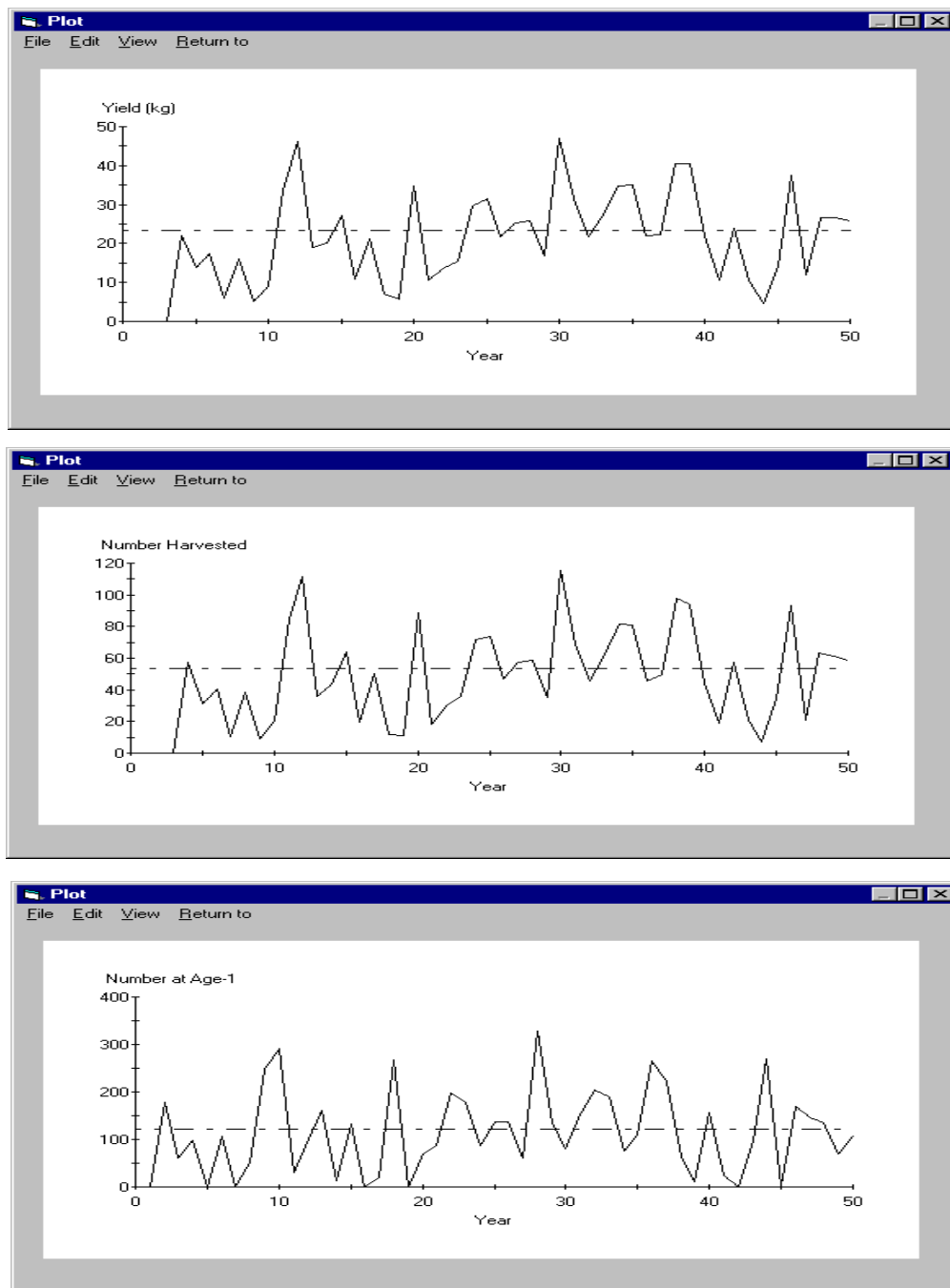
Figure 8-4. Fifty year simulations of yield (top), number harvested (middle, and number of age-1 recruits (bottom) for crappie from Weiss Lake. Because maximum age was 10 years old, model responses should be examined between Years 11 and 50. Dashed lines indicate 40 year averages for each variable. Average number of age-1 recruits was 122, not 100 because of the short duration the model was simulated with random deviates chosen for a coefficient of variation of 98% for recruitment.

rates in Years 40 to 45. Thus, with no knowledge of recruitment and not modeling a population, the success or failure of a minimum length limit in highly variable recruitment populations will be essentially a random effect. Wilde (1997) summarized evaluations of largemouth bass length and slot limits throughout the USA and found successes, failures, and no impact. Similar to our modeling results, Wilde (1997) indicated short post-length (3 to 5 years maximum) evaluation periods contributed in part to these inconsistent results.

Management recommendations and actions

Based on these findings, we recommended maintaining the 254 mm length limit on crappie. Although the local community expressed an interest in a 279 mm length limit to produce more memorable size fish, yield would not increase and angler harvest rates of crappie would decline. Growth over fishing was not apparent with the current level of exploitation, therefore, a reduction in the daily bag of 30 fish per angler was not recommended. Adjusting angler expectations to cyclic catch rates is recommended as recruitment is highly variable. Maintaining higher water levels prior to spawning will increase the probability of greater crappie year class production and dampened the effects of variable adult abundance in this reservoir.

9. EVALUATING A 406 mm LENGTH LIMIT AND A SLOT LIMIT FOR LARGEMOUTH BASS: IMPLICATIONS FOR CATCH AND RELEASE AND TOURNAMENT FISHING IN LAKE EUFAULA

Background prior to the initiation of a length limit

In July 1992, the Alabama Department of Conservation and Natural Resources (ADCNR) and the Georgia Department of Natural Resources (GDNR) jointly agreed and imposed a 406 mm (16 inch) minimum length limit on largemouth bass in Lake Eufaula which borders both Alabama and Georgia. Prior to this time, no length limit existed, and the daily bag was 10 per day and remained unchanged after July 1992. Exploitation was about 30% per year in the late 1980's and early 1990's and about 50% of the anglers practiced catch-and-release (Keefer and Wilson 1995). Recruitment was highly variable with a strong year class produced about every three years and growth rates were high. Fish obtained 304 and 406 mm in 2.0 and 4.2 years, respectively.

Modeling the largemouth bass population for data collected prior to the 406 mm length limit

From the sample files provided by FAST, open **EUFAULA_LMB_1990-92.par** for the **Yield Per Recruit Model**.

This file represents data collected from spring 1990 to 1992, prior to the initiation of the minimum length. Coefficients for the weight:length and von Bertalanffy growth equations appear. Choose **Model by varying Minimum Length** in the **Modeling Options** frame, and in the lower right frame **start**, **end**, and **step by** values of **304**, **406**, and **51** appear, indicating the population will be modeled for 304, 355, and 406 mm minimum lengths. Conditional natural mortality was set at 0.15 and a wide range of conditional fishing mortality rates were explored. For the **Lengths of Interest** frame enter **304**, **355**, and **406** for **Length 1**, **Length 2**, and **Length 3**, respectively. Load (**L**), then run (**R**) the model, and examine the plots of exploitation versus yield, number harvested, and mean total length of harvested fish by choosing **Graphical Model Output** from the **View Output** menu.
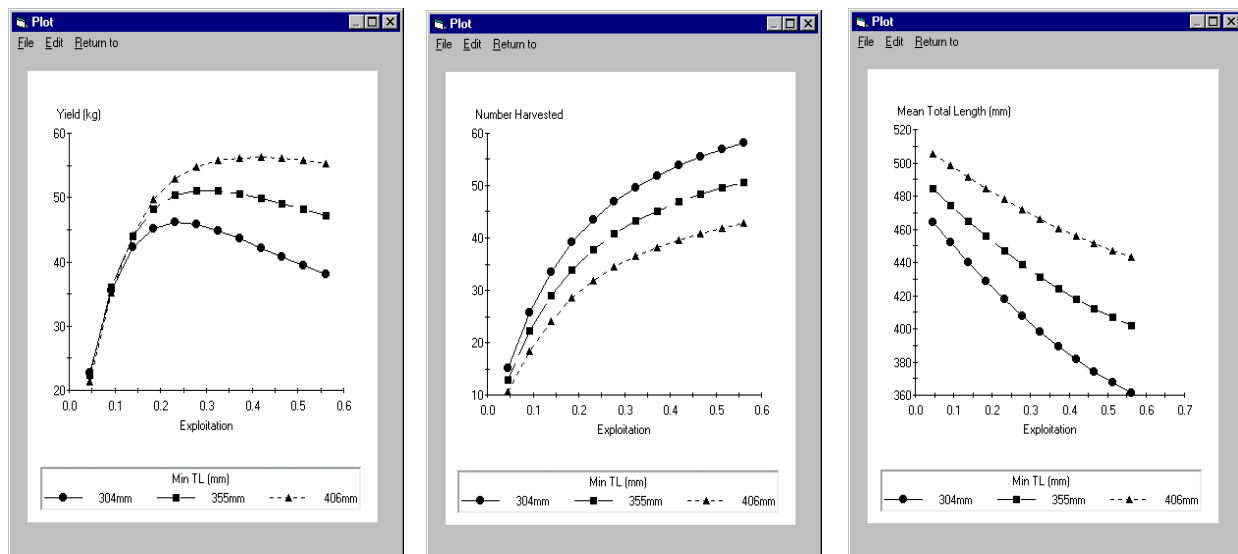
These plots show that growth over fishing would occur in this fishery when exploitation exceeded 30% for the 304 and 355 mm length limits and higher yields would be obtained with the 406 mm length limit when exploitation exceeded 20%. As expected, the number of harvested fish would be reduced with the 406 mm length limit compared to lower length limits, but the mean length of harvested fish would be substantially larger.

Using another graphics package, a plot of some of the data presented in the **Tabular Model Output** spreadsheet shows that at an exploitation rate of 30%, the number of fish entering the fishery at 406 mm would be half if a 304 mm minimum length was in effect (Figure 9-1).
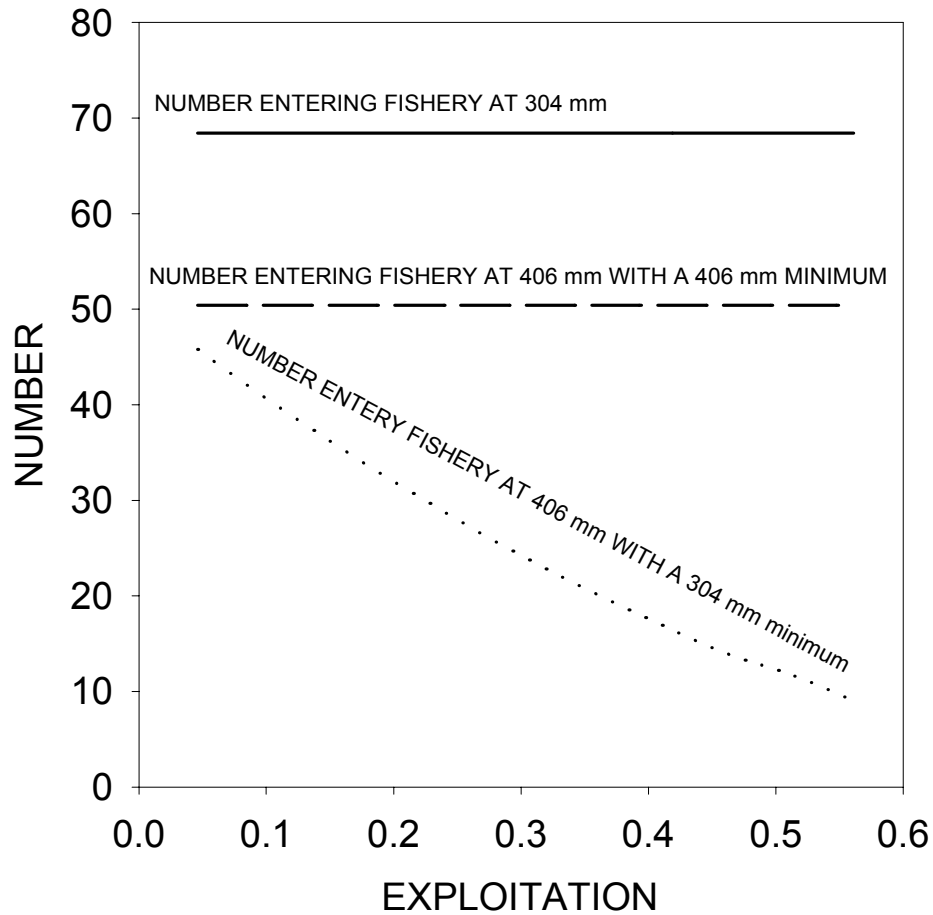
9-2

Figure 9-1.   The number of largemouth bass entering the fishery at 304 mm TL (solid line) compared to the number entery the fishery at 406 mm with a 304 mm length limit (dotted line) at varying levels of exploitation at an initial starting point of 100 age-0 fish. For reference, the number of fish entering the fishery at 406 mm when protected to this length is given (dashed line). Natural mortality was 15% and predictions were for Lake Eufaula in 1990-92.

Whether a 304 or 406 mm minimum length was imposed, the number of fish in the population 304 mm and greater would be the same. And although the number of fish that were available to harvest would be reduced with the 406 mm length limit, protection of fish less than 406 mm confers 36% (68-50/50) more fish in the population that could be caught and released between 304 and 406 mm.

To examine differences in length-structure indices among length limits, use this same sample file for the **Dynamic Pool Model**. For minimum length in the **Model Parameters** frame, enter **304**, and in the **Variable Recruitment Options** frame, choose **Fixed**, and enter **1000** for **Initial number of recruits**. For **Mortality Options**, enter **0.9** for **cm** between age 0 and age-1, and enter **0.15** for **cm** and **0.35** for **cf** for age 1 to age 13.

Thus, 100 recruits will enter the fishery at age-1 and the exploitation rate will be similar to rates reported by GDNR. Conduct the same analysis except enter 355 and 406 for **min TL** in the **Model Parameters** frame. Run the simulation for only 20 years and examine the output spreadsheets for years 14 to 20 by choosing **Tabular Model Output by Year** under the **View Output** menu. The maximum age for this simulation is 13 years, therefore the population does not reach equilibrium until the 13th year of the simulation. Length-structure indices increased with higher minimum lengths, but the greatest differences among minimum lengths were observed with relative stock densities of preferred size fish (RSD-P; Table 9-1).

Table 9-1

Minimum length (mm)	PSD	RSD-P	RSD-M
304	53	18	2
356	56	24	2
406	59	28	3

Thus, with these conditions and moderate exploitation, the 406 mm minimum length limit appeared to be a sound management decision that was made in 1992 to abate over fishing. In addition, increases in catch rates of all sizes of largemouth bass, higher yield, and improved size structure were predicted.

Background on post-length limit conditions

In the late 1990's, complaints were received by the local community and the ADCNR from organized bass fishing clubs concerning the 406 mm length limit. Fewer clubs had been fishing Lake Eufaula because tournament success had declined and only about 40% of the anglers caught at least one fish over the minimum length during tournaments. During the past 10 years, the number of tournament anglers has dramatically declined according to records maintained by ADCNR. Fishing success worsened in 1998 due to an outbreak of the largemouth bass virus and the subsequent death of many fish.

Other changes also occurred in the population and fishery over time. In 1997-99, growth rates were slower than in 1990-92, and it took a largemouth bass 2.6 and 4.9 years to reach 304 and 406 mm TL. In addition, growth of older fish appeared stagnant. For example, 5, 6, and 7 year old fish from the 1992 year class in Lake Eufaula were 432 432, and 444 mm TL in 1997, 1998, and 1999. Based on a creel survey conducted in 1999 by GDNR, 92% of the bass anglers practiced catch and release compared to about 60% during similar surveys conducted in 1990 and 1991 (Weathers et al. 2000). In 1999, total harvest was less than 2,000 largemouth bass in this 18,000 hectare reservoir (0.10 fish/hectare), and exploitation was likely less than 5-10%

(Weathers et al. 2000). In the early 1990's, when the 304 mm length limit was in place, annual harvest was about 25,000 to 30,000 fish per year. Length-frequency distributions of fish sampled in spring 1997 and 1998 before the fish kill showed few fish over 450 mm which was unexpected given the high length limit and low level of exploitation. ADCNR and GDNR requested a complete analysis of the population and provided data from standardized monitoring collections to conduct simulation modeling to predict and compare the impacts of 304 and 355 mm minimum length limits to the current 406 mm minimum length.

Re-evaluation of the 406 minimum length limit based on current conditions

To simulate current conditions, age, length, and weight data were complied for largemouth bass collected in spring between 1997 and 1999 using DC electrofishing. Model parameters derived from these data are found in the FAST sample file **EUFAULA_LMB_1997-99.par**. For the **Yield-Per-Recruit Model**, the 304, 355, and 406 mm length limits were reevaluated. Based on creel survey data from GDNR, exploitation was likely less than 10%. Thus, enter conditional fishing mortality rates from 0.01 to 0.10 with increments of 0.01. From catch-curve analysis and examination of changes in abundances of strong years classes, conditional natural mortalities of 0.20 and 0.30 can be simulated. Thus, in 1997-99, natural mortality exerted a greater force of mortality than fishing, while the opposite occurred in 1990-92. Plotting exploitation versus yield for both conditional natural mortalities showed little differences among length limits. When exploitation is low, yields typically will not vary unless length limits vary widely.

For cm's of 0.2 and 0.3, plot exploitation versus number harvested and examine the spreadsheet for the same output data. Number harvested in analogous to number caught and weighed-in at a tournament, with number caught increasing with higher fishing effort. With this analysis, the percent difference in number harvested or caught among length limits remains fixed for a range of exploitation. At a conditional natural mortality rate of 20%, 69% more fish were available for anglers to possess with a 304 than with a 406 mm minimum length limit. For the 355 mm minimum length, 33% more fish were available to anglers than with a 406 mm length
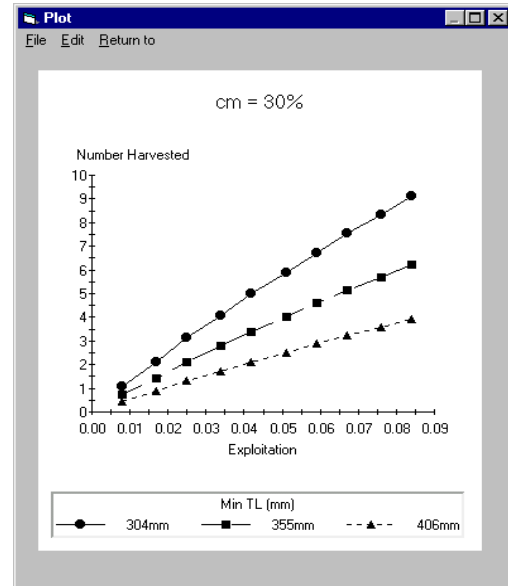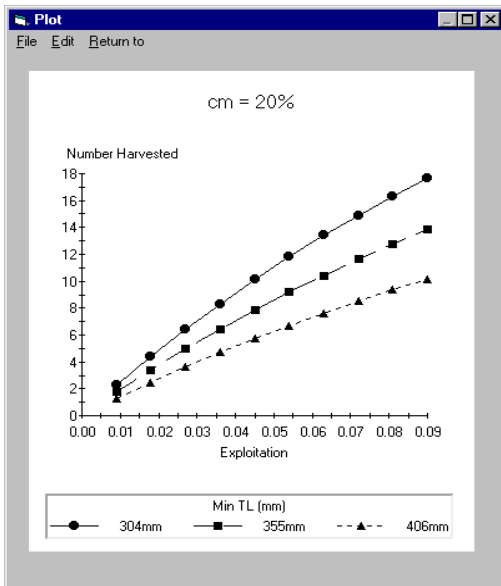
minimum.   At a conditional natural mortality rate of 30%, differences in number of fish harvested are even greater among minimum lengths. For a 304 mm minimum length, 132% more fish would be available to be kept than with a 406 mm minimum length. At 355 mm, 58% more fish would be available for possession than with the 406 mm minimum length.

Another method to determine the number of fish entering a fishery at certain length categories is by ignoring the impact of exploitation when exploitation is low. In the **Length of Interest** frame, enter **304**, **355**, and **406** mm for **Length 1**, **Length 2**, and **Length 3**, respectively. Enter zero's for **cf - Conditional Fishing Mortality** in the **start** and **end** boxes. For **cm - Conditional Natural Mortality**, enter **0.15** for **start**, **0.30** for **end**, and **0.05** for **step by**. Load and run the simulations, and examine the spreadsheet by choosing **Tabular Model Output** from the **View Output** menu. At lower conditional natural mortalities, differences between numbers at 304, 355, and 406 (mm) are low, but increase with conditional mortality as the proportion of fish removed from the population increases. Plotting this data using another graphics package shows the number entering a fishery for a specific length decreases as natural mortality increases, but a greater percentage of fish at smaller lengths are available for possession in the fishery (Figure 9-2). At conditional natural mortality rates of 15 to 30%, 1.5 to 2.3 times as many fish are available to the fishery under a 304 mm limit compared to a 406 mm limit.
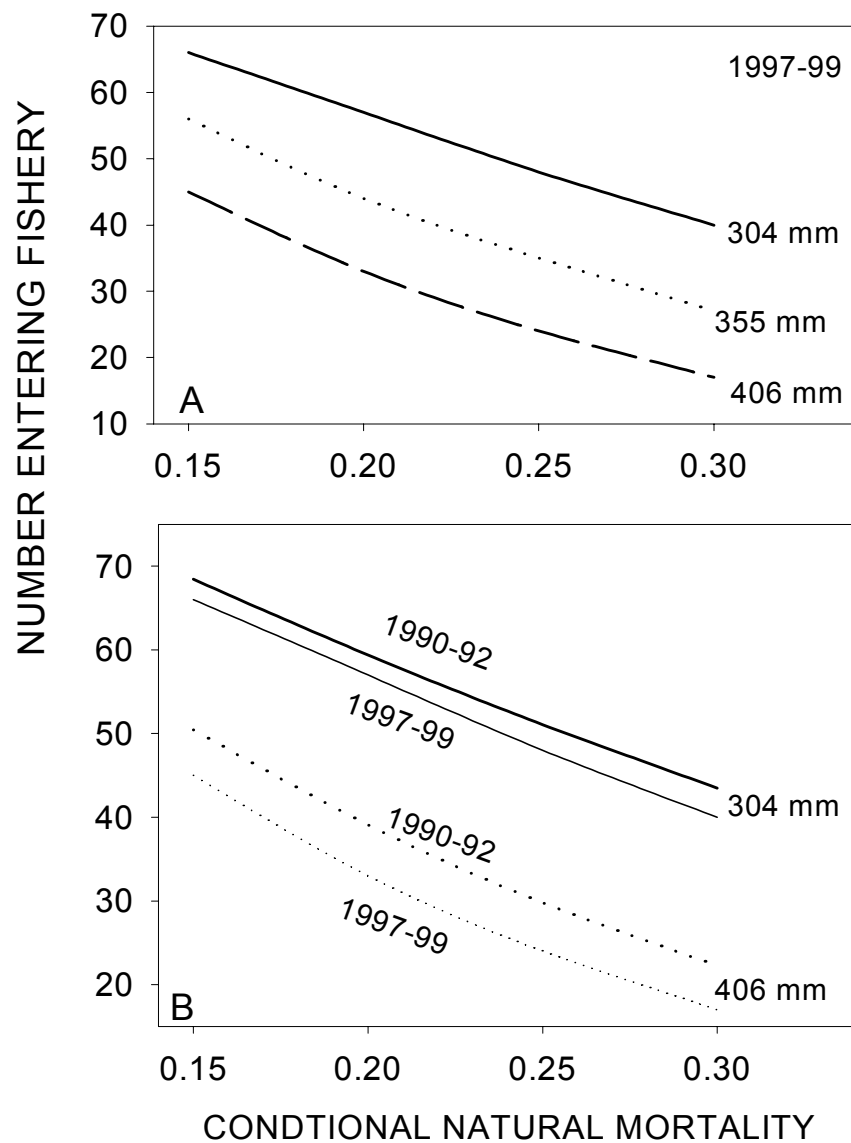
Figure 9-2. (A) Predicted number of largemouth bass entering the fishery for three different minimum lengths at various rates of natural mortality in 1997-99. (B) Comparison of predicted numbers of largemouth bass entering the fishery at 304 and 406 mm minimum lengths at various levels of natural mortality in 1990-92 (faster growth) and 1997-99 (slower growth).

From the data presented in Figure 9-1, a total of 50 largemouth bass entered the 406 mm fishery in 1990-92 when growth rates were faster and conditional mortality was 15%. In 1997-99, growth was slower and at a conditional natural mortality rate of 15%, 45 fish entered the fishery at 406 mm, a decline of 10%. At conditional natural mortalities of 20, 25, and 30%, the number of fish entering the fishery at 406 mm declined even further in 1997-99 to 33, 24, and 17 fish, respectively. Thus, with slower growth and the potential for a conditional natural mortality rate of 30%, about two-thirds fewer fish were expected to recruit to the fishery at 406 mm in 1990-92 than in 1997-99. Similarly, the number of fish entering the fishery at 304 and 406 mm at various levels of natural mortality can be compared between 1990-92 and 1997-99 (Figure 9-2). Slightly greater numbers of largemouth bass would recruit to each minimum length over a range of natural mortalities in 1990-92 because growth rates were faster than in 1997-99.

At low a low rate of conditional fishing mortality (0.1) with conditional natural mortalities at 0.2 and 0.3, the numbers of preferred and memorable size largemouth bass will be reduced at progressively lower minimum lengths. Enter these rates in the appropriate boxes for the **EUFAULA_LMB_1997-99.par** sample file in the **Yield-Per-Recruit Model** and similar to previous analyses, conduct simulations for 304, 355, and 406 mm length limits. Change lengths of interests for **Length 2** and **Length 3**, to **380** and **510**, the lengths of preferred and memorable length fish. To obtain better resolution of differences among minimum lengths for numbers of preferred and memorable size fish, increase N_o to 1,000, then load and run the model. From the **View Output** menu, select **Tabular Model Output** and **Print to Spreadsheet** the variables minimum TL, cm, cf, u, and numbers at 304, 380, and 510 (Table 9-2).

Table 9-2.

Min TL (mm)	cm	cf	u	N at 304 mm	N at 380 mm	N at 510 mm
304	0.2	0.1	0.09	565	327	70
355	0.2	0.1	0.09	565	366	79
406	0.2	0.1	0.09	565	390	90
304	0.3	0.1	0.084	402	186	21
355	0.3	0.1	0.084	402	208	24
406	0.3	0.1	0.084	402	222	28

With the 406 mm minimum length at a conditional natural mortality of 20%, 19% more (390-327/327) preferred length fish will be in the population than with a 304 mm minimum length. With a 355 mm minimum length, this difference is only 7%. At a conditional natural mortality of 30% these differences were 16% and 6%, respectively. At a conditional natural mortality rate of 20%, 29% more (90-70/70) memorable length fish would be in the population with a 406 mm minimum length than a 304 mm minimum length. The difference in numbers for these same size fish for minimum lengths of 355 and 406 mm was 14%. At the higher level of conditional natural mortality, these differences were 33 and 14% for memorable size fish. A question an analyst might ask is "would a sampling program be able to detect these percentage changes in abundances given sampling and recruitment variability?" From our experience, it would be nearly impossible to detect a decrease in abundance of preferred and memorable size fish if the minimum length limit was reduced from 406 to 355 mm. Depending on the magnitude of sampling and recruitment variability, it may also be impossible to detect these differences if the length limit was reduced from 406 to 304 mm.

The results in Table 9-1 can be repeated for data collected in 1997-99. Using the file **EUFAULA_LMB_1997-99.par** in the **Dynamic Pool Model,** set the recruitment options so that there are **1000** initial recruits and enter **0.9** for **cm** for fish between age 0 and 1 so that 100 fish will recruit to age-1. For ages 1 to 13, enter **0.2** for **cm** and **0.1** for **cf** to simulate potential conditions in the fishery in 1997-99. Enter **304**, **355**, and **406** for **min TL (mm)** and run each

simulation for 20 years. From the **View Output** menu, and **the Tabular Model Output by Year** spreadsheet after Year 13, PSD, RSD-P, and RSD-M values can be examined and compared to those computed for the conditions in 1990-92 (Table 9-3).

Table 9-3

Minimum length (mm)	1990-92 cm = 0.15 cf = 0.35			1997-99 cm = 0.20 cf = 0.10		
	PSD	RSD-P	RSD-M	PSD	RSD-P	RSD-M
304	53	18	2	45	19	3
356	56	24	2	47	20	4
406	59	28	3	47	22	4

Predicted PSD's were higher in 1990-92 than in 1979-99, even though exploitation was lower in 1979-99. FAST simulated higher numbers of stock-quality size fish in 1997-99 as fish recruited to stock-length sooner but after that growth was slower which caused more fish to accumulate in this length category. For the 355 and 406 mm minimum lengths, RSD-P was slightly higher in 1990-92 due to faster recruitment of fish through stock-length and higher growth rate of older fish. Also note, the largest changes in predicted stock density indices occurred for the 1990-92 scenario when exploitation was much greater. Thus, these stock density values are more sensitive to changes in minimum lengths when exploitation is the dominant force of mortality.

Finally, FAST can incorporate angler size selectivity for catch and harvest. Tagging and angler exploitation data were obtained from GDNR for Lake Eufaula for a study conducted in 1987. A total of 1,321 largemouth bass from 300 to 639 mm TL were tagged with T-bar anchor tags in February 1987. Anglers returned tags for a reward and data included 371 fish caught through 30 June, 1997.

Anglers selected for slightly smaller fish than were present in the population (Figure 9-3). Fifty-three percent of the tagged fish were between 300 and 400 mm, while 67% of the total number caught by anglers were within this length range. For fish 401-500 mm, and greater than 500 mm, 37 and 10% of the population were within these size groups, but percentage of fish
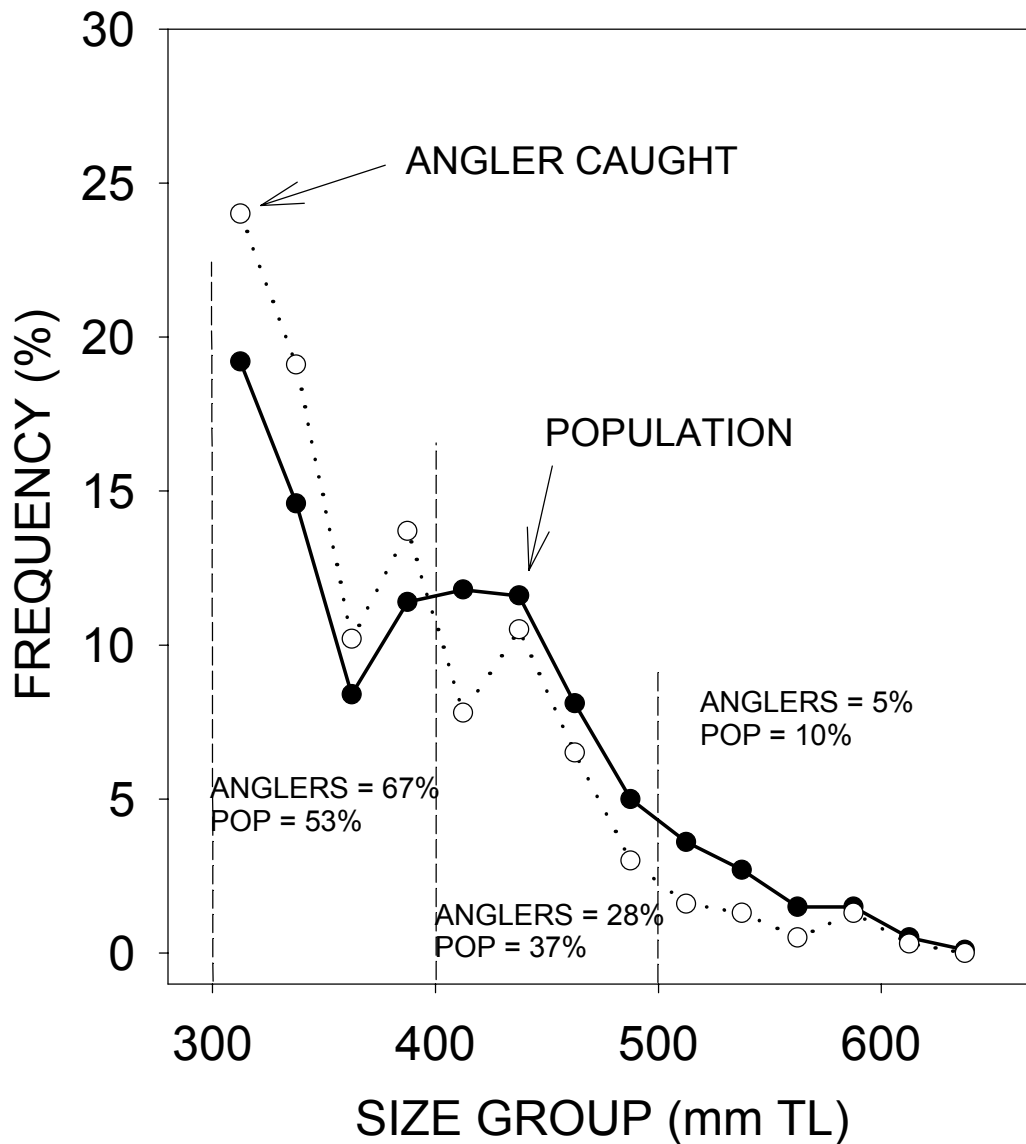
Figure 9-3. Frequency distributions of largemouth bass lengths (> 300 mm TL) tagged in Lake Eufaula in February 1987 compared to frequency distributions of fish caught by anglers from February to June 1987. Data for three different size groups (300 - 400 mm, 401 - 500 mm, and (> 500 mm) were summed and are presented.

caught by anglers in these size groups was only 28 and 5%. Thus, for largemouth bass greater than 400 mm, negative catchability of fish by anglers occurred. These differences can be simulated in FAST.

For the **Dynamic Pool Model**, open the FAST sample file **EUFAULA_LMB_1990-92.par**. For **Variable Recruitment Options**, choose **Fixed**, and enter **100** for the initial number of recruits. Similar to previous analyses, enter **0** for cm for fish between age-0 and age-1 so that 100 age-1 recruits will enter the population. For the next set of age boxes, enter **1** and **4**, **0.15** for **cm**, and **0.36** for **cf**. The value of 4 years is entered because 4.09 years is the average time it takes a fish to reach 400 mm. A cf value of 0.36 (249/695) was chosen from the exploitation study where 695 (1,312 x 0.53) tagged fish were from 300 to 400 mm and 249 (371 x 0.67) fish of this length group were harvested by anglers. With the presence of conditional natural mortality, cf values will always be higher than exploitation, but for this example, differences will be minimal.

In the next set of age boxes, enter **4** and **7** years. In this population, it takes a largemouth bass 7.23 years to reach 500 mm. Since FAST runs the dynamic pool computations from year-to-year (age-to-age), cm's and cf's are applied to whole years for ages. Thus, FAST would read 4.09 as 4 and 7.23 as 7 years, respectively. Enter **0.15** for **cm** and **0.21** [(371 x 0.28)/(1,312 x 0.37) for **cf** for mortality rates associated with this age range. Finally for the last age box, enter **7** and **13** which encompasses the rest of the life of the population. Enter **0.15** for **cm** and **0.15** [(371 x 0.5/1,312 x 0.10)] for **cf**. Enter **304** for **min TL (mm)**. Load and run the model for 20 years and examine the data in the spreadsheet found in the **Tabular Model Output by Year** for years 14 to 20. Length-structure indices, number harvested, and yield for this fishing scenario are provided.

	A	B	C	D	E	F	G	H	I
1	Year	PSD	RSD-P	RSD-M	Number	Biomass (kg)	N-harv	Yield (kg)	Num at Age-1
16	15	56	19	3	329.31	204.632	53.61	47.581	100
17	16	56	19	3	329.31	204.632	53.61	47.581	100
18	17	56	19	3	329.31	204.632	53.61	47.581	100
19	18	56	19	3	329.31	204.632	53.61	47.581	100
20	19	56	19	3	329.31	204.632	53.61	47.581	100
21	20	56	19	3	329.31	204.632	53.61	47.581	100
22	Mean	56	19	3	329.31	204.632	53.61	47.581	100
23	StdDev	0	0	0	0	0	0	0	0
24	CV	0	0	0	0	0	0	0	0

The age-structure dynamics of this simulation can be viewed by choosing **Tabular Model Output by Age** from the **View Output** menu. For a 20 year simulation, 260 lines of data will be produced (20 x 13).   Choose and add variables including year, age, length, weight, N-start, exploitation, biomass, N-harv, and yield, and **Print to Spreadsheet**.   Delete the first 13 years of data from the spreadsheet as well as years 15 to 20. Thirteen lines of data are left that show the predicted lengths and weights at each age, the number at the start of each age (N-start), the exploitation rate for that age group, and the corresponding biomass, number harvested (N-harv), and yield for each age-group. An exploitation rate of zero is listed for age-2 fish because the average length of these fish have not entered the fishery at 304 mm TL. However, a portion of this age-group was harvested as harvest number and yield is computed.

|	A	B	C	D	E	F	G	H	I
1	Year	Age	Length	Weight	N-Start	Exploitation (u)	Biomass (kg)	N-harv	Yield (kg)
171	14	1	203.36	96.097	100	0	9.61	0	0
172	14	2	281.27	283.603	85	0	24.11	19.64	8.923
173	14	3	344.7	559.034	53.7	0.334	30.02	17.95	12.654
174	14	4	396.35	890.804	29.21	0.194	26.02	5.68	6
175	14	5	438.4	1247.184	19.62	0.194	24.47	3.81	5.394
176	14	6	472.65	1602.964	13.17	0.194	21.12	2.56	4.515
177	14	7	500.53	1940.836	8.85	0.139	17.17	1.23	2.565
178	14	8	523.23	2250.478	6.39	0.139	14.38	0.89	2.114
179	14	9	541.71	2526.918	4.62	0.139	11.67	0.64	1.694
180	14	10	556.77	2768.909	3.34	0.139	9.24	0.46	1.329
181	14	11	569.02	2977.577	2.41	0.139	7.18	0.33	1.025
182	14	12	579	3155.425	1.74	0.139	5.5	0.24	0.78
183	14	13	587.12	3305.627	1.26	0.139	4.16	0.17	0.588

The tabular data presented above can be plotted with age (x-axis) against predicted variables (y-axis) by choosing **Graphical Model Output by Age** from the **View Output** menu. For this example, plot age against Number at Start of Year, Biomass, and Number Harvested. Although substantial biomass of fish greater than 6 years old exists in the population, numerical abundance is reduced and with angler size selectivity against larger fish, we predicted fish older than 6 years old comprised a very small percentage (6%) of the total harvest. This value is similar to the percentage of fish (5%)caught by anglers over 500 mm TL based on tag returns (Figure 9-3). Conversely, age-2 to age-4 fish comprised 84% of the total angler harvest.
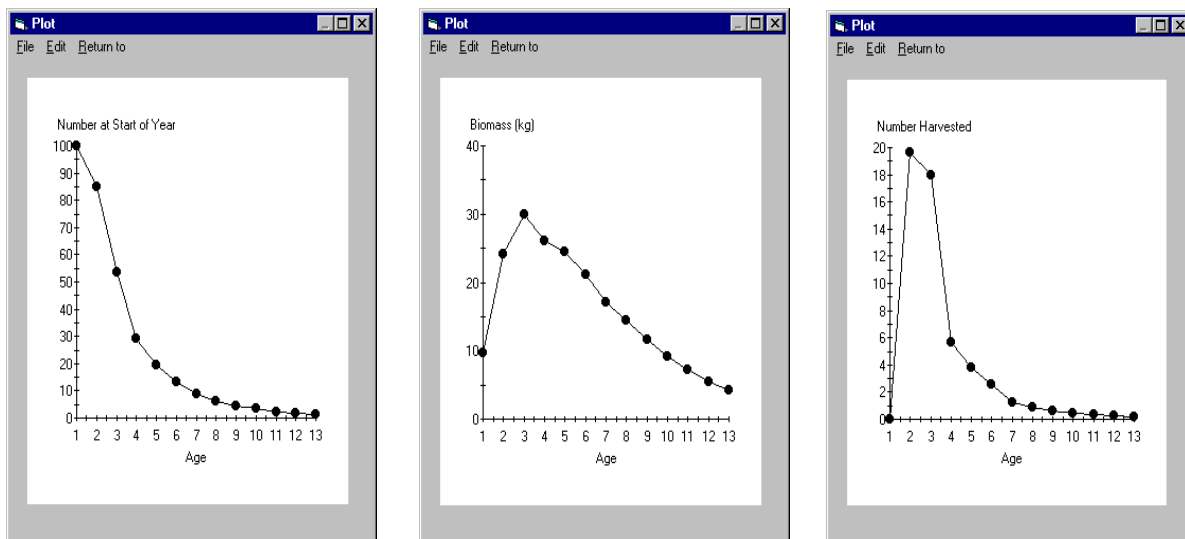
Evaluation of a 355 to 406 mm protective slot as a management alternative

In the **Yield-Per-Recruit model**, the analyst can simulate the effects of protective slot limits by choosing the **Model under Slot Limit conditions** in the modeling options frame. Slot limits fall under two general types that vary in the way they are used to manipulate and improve fisheries. The first, a protective slot, attempts to protect from harvest a length range of fish, while encouraging anglers to harvest smaller fish to reduce density, and hopefully improve growth rates of fish. This will reduce the time it takes fish to reach the upper slot length. Protective slots also prevent fish from being harvested, can increase overall abundance of catchable size fish, and improve angler catch-per-effort. For largemouth bass, a wide variety of protective slots have been used by state fish conservation agencies including 330-406 mm, 355-

432 mm, 355-457 mm, and 381-533 mm.

The second type, known as the inverted slot, is used to protect small fish from harvest, allow exploitation of some middle range of lengths, and prevent harvest of larger and older fish. This strategy attempts to increase yield by allowing the population the time to reach a greater growth potential by protecting small fish from harvest. Also, preventing exploitation of larger fish should increase recruitment by increasing the abundance large adults (primarily females). In Florida, for example, redfish harvest is permitted for fish between 457 and 686 mm. Fish smaller or larger than this must be released by anglers. In addition, because a moderate proportion of the population is protected from harvest, abundance of all lengths of fish should be higher, and angler catch rates should be greater.

One suggestion that was made after evaluating minimum length limits for largemouth bass in Lake Eufaula was to evaluate the impacts of a 355 to 406 mm protective slot on the fishery. To conduct this analysis, open the sample file **Eufaula_LMB_1997-99.par**, and choose the **Model under Slot Limit conditions** from the modeling options frame. For this option, a number of conditional natural mortality options can be simulated, but only a single set of conditional fishing mortality rates can be evaluated for fish below, within, and above a slot length limit. In the **Total Length (mm)** frame, enter **304**, **355**, and **406**, for the **recruitment**, **lower slot**, and **upper slot** boxes. In the **cf - Conditional Fishing Mortality** frame enter **0.1**, **0**, and **0.1** for **below slot**, **within slot**, and **above slot**. Thus, fish harvest and possession would be allowed for fish from 304 to 355 mm and above 406 mm. Run the model with conditional natural mortality rates of 20 and 30%. These fishing and natural mortality rates are similar to those used previously to duplicate current conditions in the fishery. Enter 100 for N_o, load and run the model, and examine the output from the spreadsheet presented in the **Tabular Model Output** menu. Choose and add the following variables to the spreadsheet: cm, Total Yield, Total Number of Fish Harvested, Total Number Dying Naturally, Yield Below Slot, Yield Within Slot, Yield Above Slot, Number Harvested Below Slot, Number Harvested Within Slot, Number Harvested Above Slot, and Number of Fish Dying Within the Slot. The spreadsheet is presented below.

	A	B	C	D	E	F	G	H	I	J	K
1	cm	Total Yield	Total Nhar	Total Ndie	Yield Belo	Yield Withi	Yield Abov	Nharv Belo	Nharv Withi	Nharv Abov	Ndie Withi
2	0.2	17.958	14.444	85.556	2.586	0	15.371	5.35	0	9.1	9.96
3	0.3	7.106	7.039	92.961	1.71	0	5.396	3.56	0	3.48	9.05

Sheet1

At a conditional natural mortality rate of 20%, the total yield and harvest is more than twice as great than at a conditional natural mortality rate of 30%.   From this analysis, this protective slot would have greater utility at lower rates of natural mortality. Summing the total number of fish harvested and dying naturally will equal 100 fish, which is N_o. Note that the number dying within the slot is slightly greater at a cm of 205 than at 30% because fewer fish recruit to 355 mm when cm is 30%.

However, for tournament anglers, a protective slot usually confers a minimum length of fish at the upper slot length that can be possessed in a tournament. By summing the number harvested and number dying above the slot, the analyst can determine how many fish will be available for anglers to posses over the upper slot length. At conditional natural mortalities of 20 and 30%, 29.87 and 15.51 fish will recruit into the fishery at 406 mm under these two scenarios.

 Greater benefits of this slot could be obtained if growth rates increased, particularly of younger fish. Fish would recruit to 304 mm earlier and the impact of natural mortality would be less for the time these fish are between the 355 and 406 mm slot. For example, assume a public relations and education program could encourage anglers to harvest and remove fish between 304 and 354 mm. If exploitation could be increased to the rates measured in the late 1980's for these length fish, growth rates could increase and confer an increased abundance of fish greater than 406 mm. For this example, open the sample file **Eufaula_LMB_1990-92.par,** which has parameters based on data collected when growth was faster. Enter the same slot limit sizes and cm's, but enter **0.3** for conditional fishing mortality for the lower slot. Load and run the model again, and compare the results in the table below to those in the table above.

	A	B	C	D	E	F	G	H	I	J	K
1	cm	Total Yield	Total Nharv	Total Ndie	Yield Below	Yield With	Yield Above	Nharv Below	Nharv Within	Nharv Above	Ndie Above
2	0.2	22.956	23.082	76.918	6.787	0	16.169	14.2	0	8.89	19.98
3	0.3	10.82	13.581	86.419	4.697	0	6.124	9.87	0	3.71	12.74

Sheet1

For these two conditional natural mortality rates, a total of 28.87 (9.26 + 19.61) and 16.45 (3.75 + 12.70) would recruit to the 406 mm minimum size. These predicted values for conditions of faster growth and greater exploitation of pre-slot length fish are nearly identical to those predicted for conditions of slower growth and lower exploitation of below slot length fish. Higher values of conditional natural mortality could be simulated and these would predict even lower abundances of fish entering the population at 406 mm.

If increased angler yield for both weight and numbers are desired management goals, and higher exploitation of below slot length largemouth bass would lead to the faster growth rates observed in 1990-92, then this slot limit could be recommended. Predicted total yields at 20 and 30% conditional natural mortality rates were 23.0 and 10.82 kg for the faster growth and higher exploitation scenario, somewhat higher than 18.0 and 7.1 kg for the slower growth and lower exploitation scenario. In addition, total harvest numbers were about twice as great with higher exploitation of below slot fish and faster growth, compared to slower growth and lower exploitation.

Finally, these slot limit results can be compared to the single current 406 mm minimum length limit for conditions observed in 1997-99. Enter **406** for **Min TL (mm)** for the 1997-99 Eufaula largemouth bass sample file, and run the model for conditional natural mortality rates of 20 and 30% for a wide range of conditional fishing mortality rates. A total of 33 and 17 largemouth bass will enter the fishery at 406 mm at conditional natural mortality rates of 20 and 30%, slightly higher than predicted for the two 355 to 406 mm slot limit scenarios. Yields for both levels of natural mortality would peak at about 33 and 15 kg at exploitation levels of greater than 50%. Given the current high level of catch and release and the growing trend toward less consumptive

largemouth bass fisheries (i.e., tournaments), this level of exploitation would be unlikely in Lake Eufaula. Therefore, we conclude that a 355-406 mm protective slot limit would not increase abundance and hence, the catch of tournament length fish in Lake Eufaula.

Management recommendations and actions

We recommended to ADCNR and GDNR that the minimum length limit be reduced for largemouth bass in Lake Eufaula from 406 mm to either 304 or 355 mm. A 304 or 355 mm minimum length would increase the number of fish available for anglers to keep by 70-130% and 30-60%, respectively. Exploitation is currently extremely low, as most anglers practice catch-and-release. Growth rates decreased after the 406 mm length limit went into effect and natural mortality rates were likely higher. Lower length limits will likely encourage greater tournament participation that will provide economic benefits to the local region. Negative effects of reduced lengths limits include lower abundances of preferred and memorable size fish if exploitation is about 8-9%. Protective slot length limits would not increase the abundance of fish greater than 406 mm in the population. The GDNR and the ADCNR agreed to lower the minimum length limit for largemouth bass to 355 mm and this change went into effect on 1 November 2000.

10. USE OF THE SPAWNING POTENTIAL RATIO TO EVALUATE RECRUITMENT OVER-FISHING OF STRIPED BASS IN THE CHESAPEAKE BAY

Background

The recovery of the once nearly depleted Chesapeake Bay striped bass *Morone saxatilis* fishery has been viewed as a one of the most successful examples of effective fisheries management (Field 1997; Richards and Rago 1999). Extremely poor commercial landings and depressed juvenile production in the 1970s and 1980s (Figure 10-1) led to increased research, management and legislative efforts aimed at recovering the beleaguered stock. By 1995, the Chesapeake Bay stock had been declared as fully recovered (Richards and Rago 1999).

Three broad hypotheses were formulated to explain this decline: habitat degradation, changes in ecological interactions, and over-fishing. However, evidence strongly suggested that during the 1970's, excessive fishing mortality (30-60%/year) at existing low minimum lengths (30-36 cm TL in Chesapeake Bay; 43 cm TL along the Atlantic coast) had exceeded reference points for stock collapse and likely led to recruitment over-fishing (Richards and Rago 1999).

By 1985, regulatory efforts were made to protect the Chesapeake Bay's 1982 year-class, which was only of average size but was the strongest since 1978 (Figure 10-1). These measures required states to either institute fishing moratoria or progressively increase minimum length limits to exceed the 95th percentile for size of females at the age of 95% maturity (97 cm TL, age-8) by 1990. The 97 cm length limit was essentially a closure since few fish in the stock exceeded the length limit (Richards and Rago 1999). This was done to protect 95% of the females of the 1982 and later year-classes until 95% had an opportunity to spawn at least once, essentially increasing the spawning potential ratio of the stock.

A high juvenile abundance index in 1989 (Figure 10-1) led to a re-opening of the fishery under a restrictive basis. Although the Maryland juvenile abundance index decreased the following year, 1991 began a trend of increased annual juvenile indices and increased commercial landings that continued through 1996 (Richards and Rago 1999).

In this example, we explore the use of the spawning potential ratio (SPR) to identify why the Chesapeake Bay striped bass fishery decline in the 1970s and 1980s and how reducing
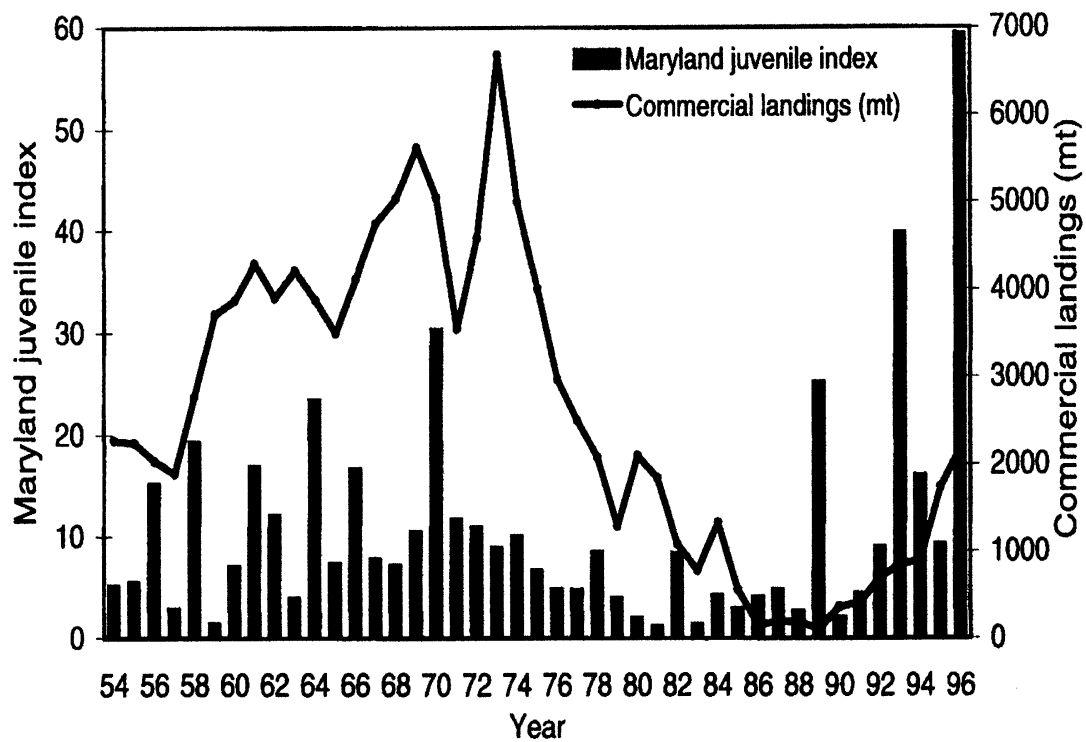
Figure 10-1. Indices of juvenile striped bass abundance for Maryland's waters of Chesapeake Bay and commercial landings (metric tons, North Carolina through Maine) of striped bass, 1954-1996. Reprinted from Richards and Rago (1999).

exploitation and increasing minimum lengths led to its recovery in the 1990s. For a more detailed discussion of the spawning potential ratio, refer to Chapter 5 of this manual.

Modeling the Chesapeake Bay striped bass population

The Decline

Using the Yield-Per-Recruit (YPR) model, open **Striper_CB_1970s.par** from the sample files offered by FAST, and choose to **Model by varying Minimum Length**. Data correspond to conditions in the 1970s and early 1980s. Coefficients for the weight:length and von Bertalanffy growth equations were obtained from the literature for female striped bass from the Chesapeake Bay (Mansueti 1961). These coefficients were based on fork length (FL) measurements. Since regulations for the fishery were based on total lengths and model parameters were based on fork lengths, all simulations were run using fork lengths. The conversion used was FL = 0.93*TL (Merriman 1941). The maximum age was also obtained from the literature (Merriman 1941). The simulation modeling was conducted using the conditional mortality rate of 0.18, since the actual management decisions made for this fishery were based on that level of mortality (M = 0.20; Richards and Rago 1999).

Under **Compute SPR?**, click on **Yes**. A **Reproductive Options** window will appear. Open the **Striper_CB_fecund.fec** sample file. The fecundity-length relation was derived from data presented in Lewis and Bonner (1966). The best fit for this relation was linear and in the form:

$$\text{Fecundity} = 2{,}777.08(\text{FL}) - 1{,}057{,}029 \qquad\qquad 10{:}1$$

where FL = fork length of females in mm, and fecundity is the number of mature ova. The percent of females spawning annually by age was obtained from Berlinsky et al. (1995) and the male:female ratio of 50:50 was chosen arbitrarily. Click **OK** and return to the main window.

Conditional fishing mortality ranges from 0.0 to 0.7 and varies by 0.05 for this simulation. These values encompass the estimated annual fishing mortality values (30 -60%; cf = 0.33 - 0.67) reported for the coastal striped bass fishery during the 1970s for all ages and sexes combined (Richards and Rago 1999). Three length limits are evaluated for this simulation to simulate the fishery of the 1970s and early 1980s. The minimum length limits of 300-360 mm TL in Chesapeake Bay and 430 cm TL along the Atlantic coast correspond to 280-340 mm FL and 400 mm FL, respectively. Clicking on the **L** button loads the parameters and readies the program to run the simulation, performed by clicking the **R** button. The mouse pointer icon will change to an hourglass while the simulation is running and will return to a pointer when computations have ceased.

Once the program has finished running, choose **Graphical Model Output** from the **View Output** menu. Plot **Exploitation** versus **Yield**, choose **Plot by TL**, and click **Plot the Data**. The plot shows that growth over-fishing was occurring for this fishery at exploitation rates greater than about 15%, regardless of the minimum length limit. Select **Choose New Variables** under the **Return to** menu, and plot **Exploitation** versus **Spawning Potential Ratio**. Notice that at all ranges of length limits, SPR's were well below the 20-30% level suggested by Goodyear (1993) at the levels of reported exploitation for the period.
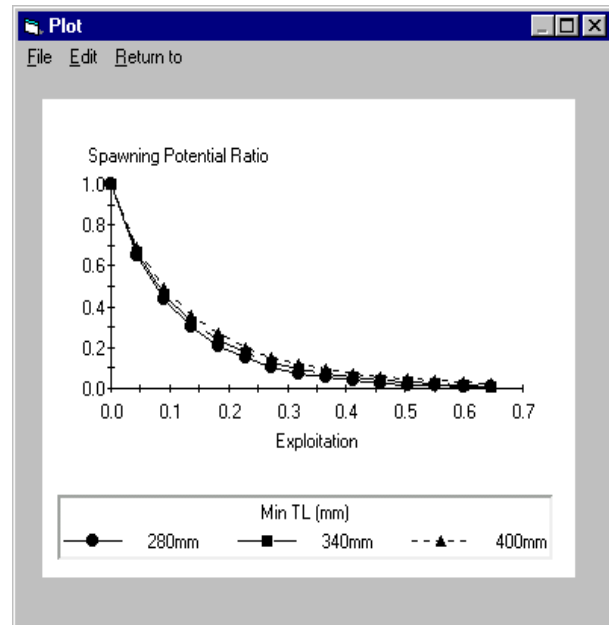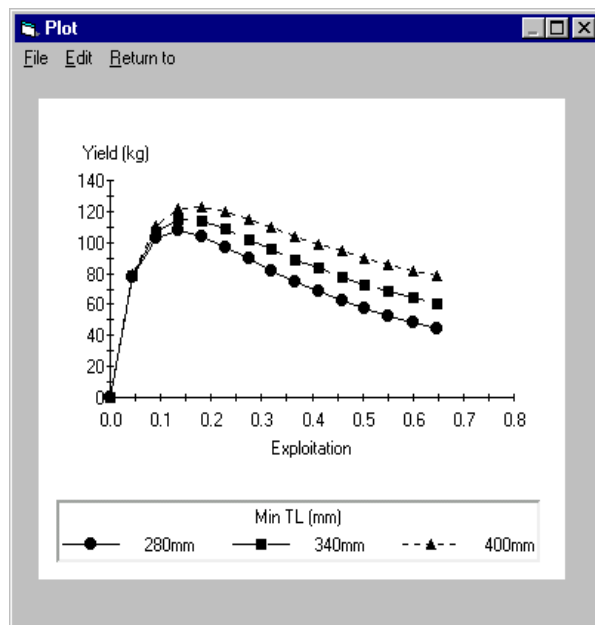
To gain a better understanding of how over-exploitation can lead to the low SPR values indicative of recruitment over-fishing, click on the **DP** button to switch to the Dynamic Pool model main window. Open the same file (**Striper_CB_1970s.par**) and choose the **Fixed** recruitment option with 1000 for the initial number of recruits. Under the **Mortality Options** notice that there is no mortality from age-0 to age-1. This simply means that 1000 age-1 recruits are set to enter this population each year. The **cm = 0.18** is the same as before and the **cf = 0.33** is equivalent to an exploitation rate of 30% for this example. The minimum TL of 400 mm is actually the minimum length of 400 mm FL for the Atlantic coastal fishery during the 1970s and early 1980s. Similar to the YPR model, click **L** and then **R** to run the simulation.

When computations cease, choose **Graphical Model Output by Age** from the **View Output** menu. Plot **Age** versus **Biomass** for any year beyond the maximum age of the population (30 years). Notice how the population biomass drops off precipitously after age-4, indicating that older, more fecund females are being removed from the population at a rather rapid rate. Compare this to the age-specific population biomass when no exploitation exists. This can be done by closing the plot window and re-running the model with a conditional fishing mortality of 0.00 instead of 0.33.
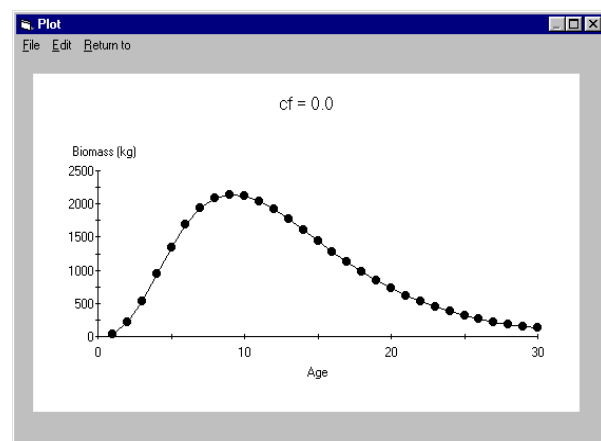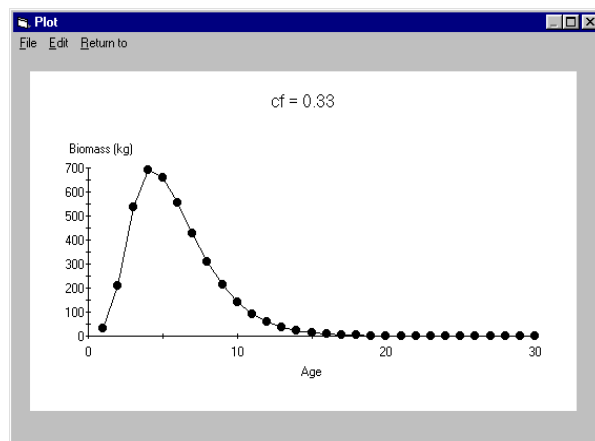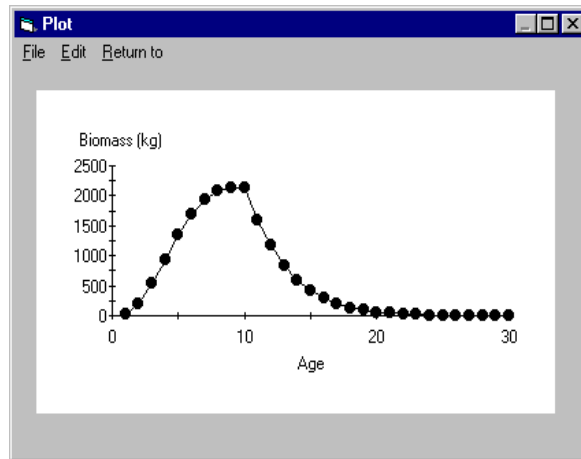
The Road to Recovery

From the Yield-Per-Recruit model main window, open the **Striper_CB_1985.par** file from the sample files folder and choose the **Fixed Minimum Length** modeling option. Notice that the model parameters are essentially the same as those for the example above since the same population is being modeled. However, for this portion of the example, the minimum length limit is fixed at 902 mm FL to simulate the 970 mm TL protective length limit initiated in 1985. Run the simulation, then plot **Exploitation** versus **Yield** and **SPR** as in the previous portion of the example. For the yield plot, notice that growth over-fishing did not occur at any level of exploitation, since the maximum growth potential of the population was achieved prior to the start of fishing. For the SPR plot, notice that SPR never even comes close to approaching the critical level of 20-30%, regardless of the level of exploitation.
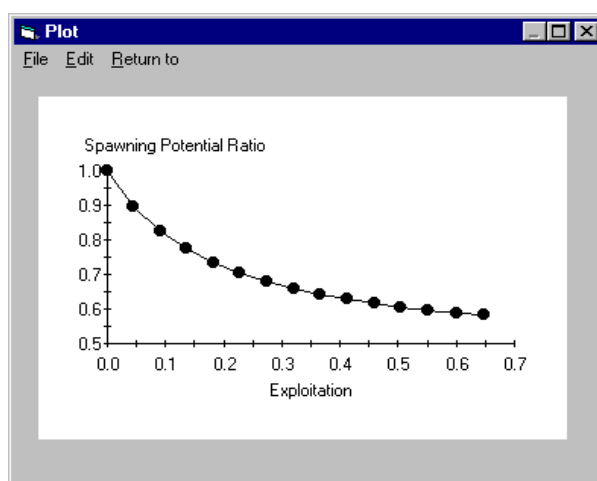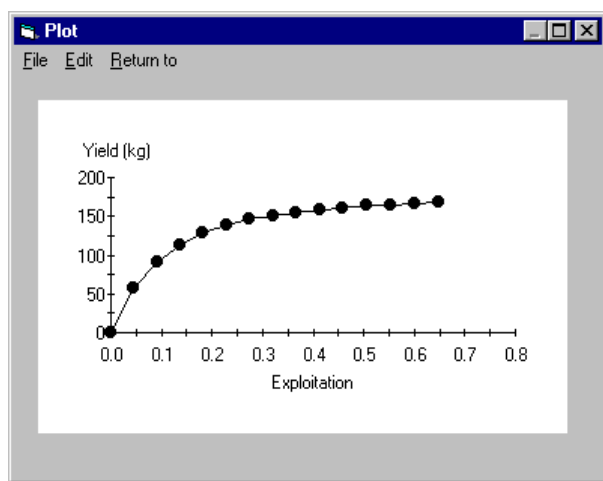
Similar to the previous portion of the example, switch to the Dynamic Pool model and open the **Striper_CB_1985.par** file. The conditional fishing mortality of 0.22 corresponds to an exploitation rate of 20% for this simulation. Run the simulation as in the previous portion of the example and plot **Biomass** versus **Age** for a year that exceeds the maximum age of fish in the population (30 years). Compare this plot to that produced using the 1970s simulation and notice the increase in the biomass of fish age-7 and older, fish that likely contribute heavily to the spawning stock.

The Recovered Stock

As previously mentioned, the fishery was re-opened in 1990 and was declared fully recovered in 1995. This portion of the example will simulate the population under the regulations in place at the time of stock recovery. From the Yield-Per-Recruit model main window, open the **Striper_CB_1995.par** file from the sample files folder and choose the **Variable Minimum Length** modeling option. Again, notice that the model parameters are essentially the same as those for the examples above. However, for this portion of the example two minimum length limits of 428 and 660 mm FL will be used to simulate the length limits initiated in 1990, 710 mm TL along the coast and 460 mm TL in Chesapeake Bay. The target exploitation in 1995 was set at an interim rate of 26%, with an ultimate level of 30% (Richards and Rago 1999). Run the simulation, then plot **Exploitation** versus **Yield** and **SPR**, by **TL** as in the first portion of the example. For the yield plot, notice that at exploitation rates of 26-30% growth over-fishing did occur for the lower minimum length limit. However, for the higher length limit of the coastal fishery, growth over-fishing was not evident. For the SPR plot, notice that at exploitation rates of 26-30% SPR is below the critical level of 20-30% for the lower minimum length limit, but above the critical level for the higher length limit of the coastal fishery. These numbers appear feasible for the continued propagation of the stock considering that the proportion of anadromous striped bass that leave estuarine waters to join the coastal fishery increases with body length (Dorazio et al. 1994) and seasonal closures of the fishery also help to protect the spawning stock from over-exploitation (Richards and Rago 1999).
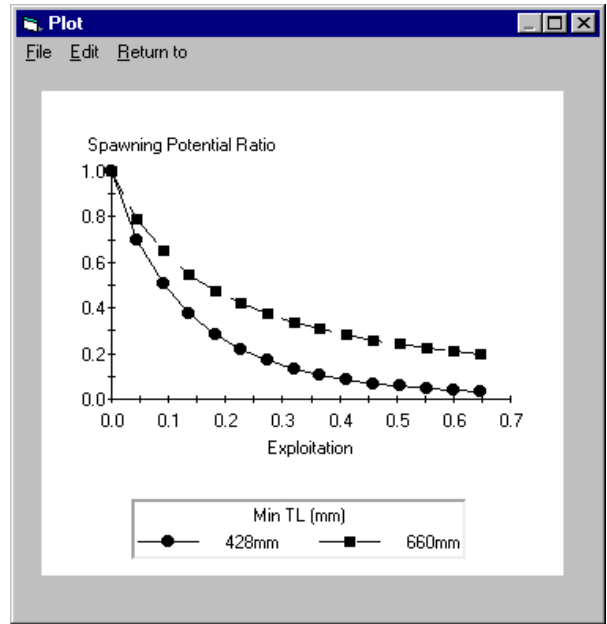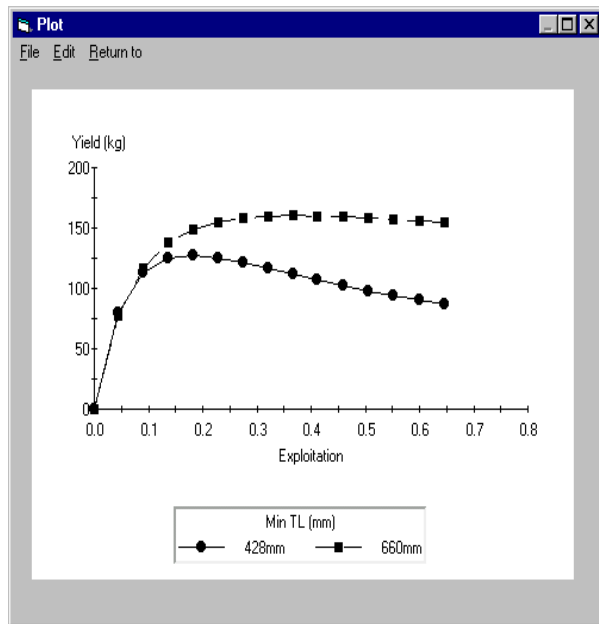
Contour Plots

As a final portion of this example, the use of contour or isopleth plots will be examined. From the Yield-Per-Recruit model main window, open the **Striper_CB_1985.par** file from the sample files folder and choose the **Variable Minimum Length** modeling option. Again, notice that the model parameters are essentially the same as those for the examples above. However, for this portion of the example simulations will be run over a range of minimum lengths from 200 mm to 1000 mm FL, stepping by increments of 10 mm. Also, change the **step by** value for **conditional fishing mortality** to 0.01. Click on **L** to load the parameters and notice that 5,751 lines of data will be produce by this simulation. Thousands of lines of data are needed to produce smooth contour plots. Run the simulation (this may take some time), then choose **SPR Contour Plot** and **Yield Contour Plot** under the **View Output** menu. These plots provide a good visualization of the synergistic effects of exploitation and minimum length on SPR and yield. These plots also show that 1995 conditions for the coastal fishery (660 mm FL; 26-30% exploitation) provided for maximum yield and SPR values that exceed 30%. The contour plots provided by FAST can aid the analyst in identifying target levels of exploitation and minimum lengths to achieve the management goals of a fishery.
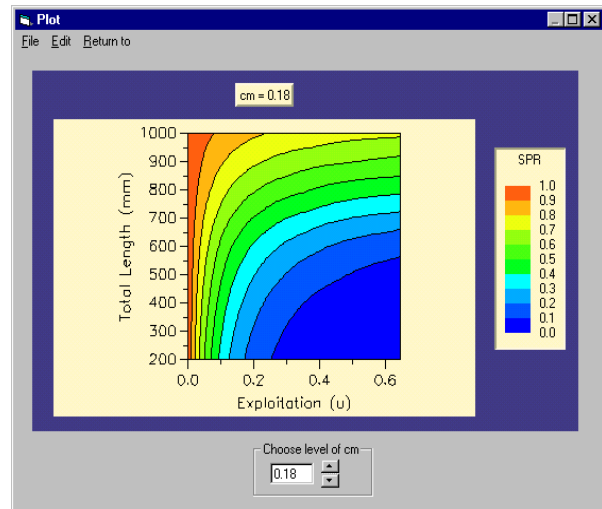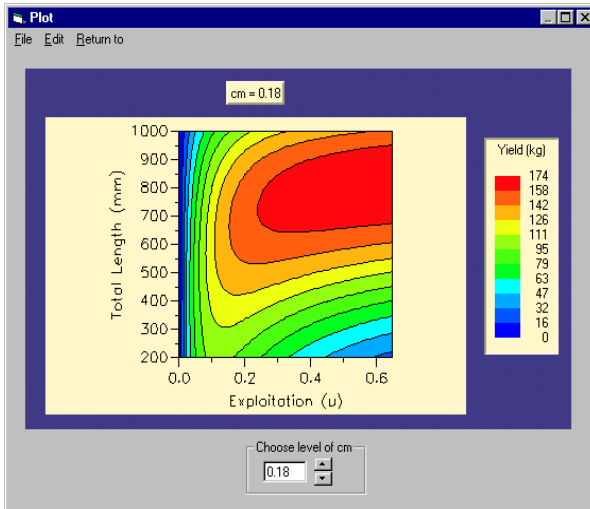
An alternative evaluation using transitional SPRs

The previous portion of this chapter evaluated the use of static SPR analysis to examine the decline and subsequent recovery of the Chesapeake Bay striped bass fishery. A recent addition of the FAST simulation model is the ability to compute transitional SPR (tSPR) and weighted-transitional SPR (wtSPR; see Chapter 5). This remainder of this chapter will be devoted to examining the use of these two measures of SPR in the evaluation of this fishery. For a complete description of the background of this fishery, refer to the previous sections of this chapter.

Begin by opening the **Striper_CB.par** file into the Dynamic Pool main window. This file contains the model parameters required to run the simulation model. For a description of how these model parameters were derived, refer to the previous sections of this chapter.

From the **Compute SPR?** frame, click on **Yes**. A **Reproduction Options** window will appear. Open the **Striper_CB_fecund.fec** sample file if it is not already open. The fecundity-length relation was derived from data presented in Lewis and Bonner (1966). The best fit for this relation was linear (see Equation 10:1). The percent of females spawning annually by age was obtained from Berlinsky et al. (1995) and the male:female ratio of 50:50 was chosen arbitrarily. Click **OK** and return to the main window.

For this example, we will use values from the Maryland juvenile index (Figure 10-1; Richards and Rago 1999) as inputs into the customized recruitment option. To do this, choose the **customized recruitment** option radio button and an embedded spreadsheet will appear. Activate the spreadsheet and open the sample file **MJI.vts**. This will fill the worksheet with data that closely approximates the values of the Maryland Juvenile Index multiplied by 100. After the file is opened, close the active form of the spreadsheet to return to the embedded form. Note that for years 1 to 53, the worksheet contains a fixed value of 500 initial recruits since no data was available for years prior to 1954. The data for years 54 to 96 correspond to the years 1954 to 1996 in Figure 10-1.   After year 96, the worksheet contains a fixed value of 2500 initial recruits and this number is entirely arbitrary. To return to the main window of the Dynamic Pool model, click the **Accept Values** button.

To see how the measures of tSPR and wtSPR change in response to different management and regulatory actions, the customized mortality option will be used. To do this, choose the **customized mortality** option radio button and an embedded spreadsheet will appear. Activate the spreadsheet and open the sample file **CB_custom_mort.vts**. This will fill the worksheets with data corresponding to conditional fishing (cf) and conditional natural (cm) mortality rates for each age and each year of the simulation. After the file is opened, close the active form of the spreadsheet to return to the embedded form. Select the worksheet labeled **cm** and note that the value for cm (0.18) is fixed for each age and year of the simulation since we are making the assumption that the natural mortality rate remains constant across all ages and years.

Next, select the worksheet labeled **cf** and notice that for the years 1 to 58, the value of cf is 0.00 for ages 0 to 2, and is 0.17 for ages 3 through 30.   The cf for age-3 and older fish is 0.25 for years 59-67, 0.38 for years 68-73, and 0.54 for years 74-80.   The cf of 0.54 for the late 1970s was obtained from estimates presented in Richards and Rago (1999) and the rates for previous periods were estimated from commercial landings data (Figure 10-1) under the assumption that commercial harvest was proportional to fishing mortality during the 1950s and 1960s. The absolute levels of fishing mortality during these periods are poorly known, but were assumed to have increased over time from the 1960s through the 1970s (Richards and Rago 1999).

For years 81 to 84, the value of cf is 0.00 for ages 0 to 4, and is 0.54 for ages 5 through 30.

This corresponds to an exploitation rate of 50% for fish age-5 (569 mm) and larger, generally the conditions of the coastal fishery between 1981 and 1984. In 1985, the minimum length limit for the fishery was raised to 902 mm FL. Therefore, the values of cf for the years 85 to 89 are 0.00 for ages 0 to 9 and 0.22 for ages 10 through 30. These values correspond to an exploitation rate of 20% for fish age-10 (902 mm) and larger. This was essentially a moratorium on harvest, since very few fish in the stock exceeded this length (Richards and Rago 1999).

The fishery re-opened in 1990 under a restrictive basis and the gradual increase in values of cf for years 90 to 94 reflect this. By 1994, fishing mortality levels were near the restoration target of F = 0.25 (cf = 0.22; Richards and Rago 1999). The fishery was declared fully recovered in 1995 with an interim fishing level set at F = 0.33 (cf = 0.28) and an ultimate level of F = 0.40 (cf = 0.33), but most states' commercial fisheries harvested less then their quota in 1995 (Richards and Rago 1999) so cf was set to 0.22 for year 95 of the simulation. The values of cf for years 95 and later in the custom mortality worksheet reflect this management scenario. To return to the main window of the Dynamic Pool model, click on Accept Values from the menu bar.

Once the preceding steps have been completed, the simulation is ready to run. Note that the value for minimum length is 200 mm. This ensures that the age-specific values for cf entered in the custom mortality spreadsheet will not be over-ridden by a high minimum length (see Chapter 4). Clicking on the **L** button loads the parameters and readies the program to run the simulation, performed by clicking the **R** button. The mouse pointer icon will change to an hourglass while the simulation is running and will return to a pointer when computations have ceased.

Once the program has finished processing, choose **Graphical Model Output by Year** from the **View Output** menu. Plot **Total Yield (kg)** versus **Year**. A plot similar to the one below should appear. The x-axis and y-axis scaling on the plot below was altered by selecting **Chart Elements** from the **Edit** menu of the Plot window. Notice that for years 54 through 96, this plot is similar to the plot of commercial landings depicted in Figure 10-1.
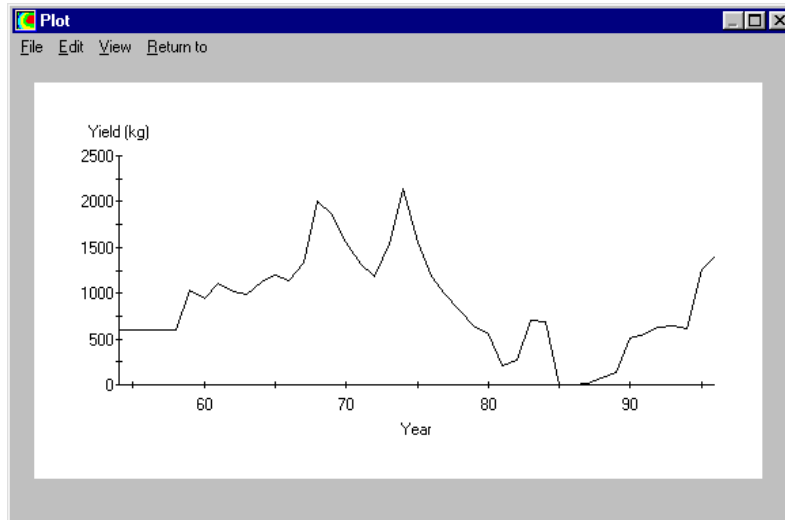
Next, plot **Transitional SPR** versus **Year**. A plot similar to the one shown below should appear.
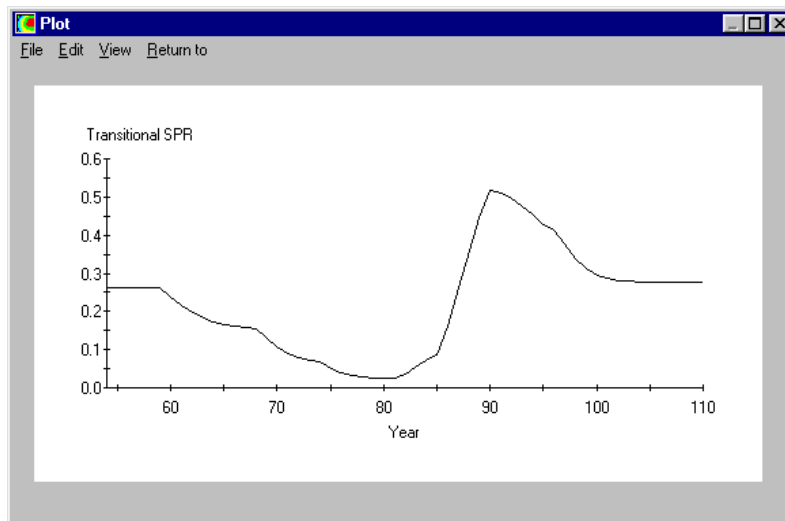
Although not depicted in the plot above, notice that tSPR is not computed until the 31st year of the simulation. This is because full recruitment to all ages does not occur until this time. From year 31 to year 58, tSPR remained constant at a value of 0.26 since fishing mortality was constant during that time. The decline in tSPR commencing in year 59 was associated with the increase in fishing mortality that occurred during the 1960s and 1970s. It also was associated with a period of increasing commercial catch that occurred during the 1960s and early 1970s. The tSPR fell below 20% by year 62 of the simulation and reached its lowest point (0.024) in year 80, just prior

to the change to a more restricted fishery in 1981. From year 82 to year 85, a gradual increase in tSPR is seen as 3 and 4 year old fish were protected from harvest from 1981 through 1984. The increase in the minimum length limit to 902 mm FL and reduced exploitation that was implemented from 1985 through 1989 caused the more dramatic rise in tSPR from 1986 to 1990.

The re-opening of the fishery in 1990 under a restrictive basis was associated with a gradual decline in tSPR between year 91 and year 95. The decline in tSPR starting in year 96 and the eventual return to an equilibrium level of 0.275 by about year 108 was associated with the declaration of the fishery as being fully recovered in 1995 and an eventual increase in exploitation rate to 30% for fish age 6 and older.

A similar pattern over time can be observed for wtSPR. However; since wtSPR is weighted by the number of fish in each age during each year, this metric will respond not only to changes in fishing mortality, but will also fluctuate with variations in recruitment or abundance at age. To see this, select **Choose New Variables** from the **Return to** menu of the Plot window. Once done, simply choose to plot **Weighted-Transitional SPR** versus **Year**. A plot similar to the one shown below should appear.
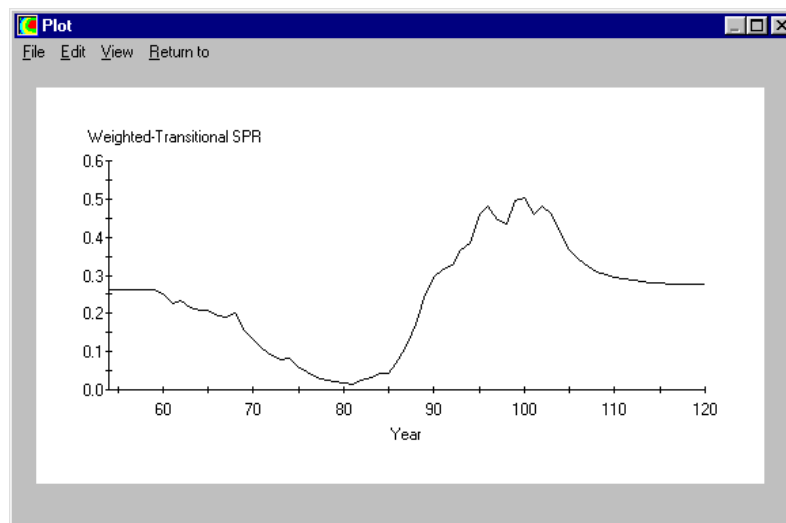
Notice again that wtSPR is not computed until the 31st year of the simulation. Also, note that wtSPR remains constant until year 60 even though recruitment began to fluctuate beginning in year 56. Recall that the time to reach partial sexual maturation for this population was age-4.

Therefore, the cohort produced in year 56 would not contribute to the computation of SPR until four years later (year 60).

Similar to the response of tSPR to changes in fishing mortality, wtSPR begins to show a gradual increase beginning in year 82 in response to the more restrictive harvest regulations that commenced in year 81. However; comparing the two plots, the values of wtSPR are lower than those of tSPR for years 82 through 94. Although tSPR reaches a peak at 0.517 in year 90, associated with the end of a four year period where the minimum length limit was extremely high (902 mm FL) and exploitation was quite low, wtSPR does not peak until year 100. The reason for this is that wtSPR is sensitive to abundance (i.e., biomass) at age, whereas tSPR is not. So even though the fishery was being exploited the least during the years 85 to 89 (leading to high tSPR values), the substantial increase in spawning stock biomass that resulted from the reduced exploitation was not manifested until years later, once those protected cohorts reached older ages. To view this relationship, return to the main Dynamic Pool window and choose **Tabular Model Output by Year** from the **View Output** menu. From the list of variables, choose to print **Total Biomass**, **Transitional SPR** and **Weighted-transitional SPR** to the spreadsheet. Select **Freeze Header Row** from the Spreadsheet menu and scroll down to years 80 to 110. You will notice that tSPR begins to respond more rapidly to the restrictions placed upon the fishery, whereas population biomass and wtSPR respond more slowly as changes in fishing mortality work their way through the age structure of this relatively long-lived population.

Summary

The Chesapeake Bay striped bass decline and subsequent recovery provides an example of how the spawning potential ratio can be used as another tool in the management of exploited fish populations. Although much of the SPR work to date has focused on pelagic marine species, we feel that SPR certainly has applications for a number of freshwater, estuarine, and coastal marine fisheries. Species with recruitment limited more by parental abundance than by environmental factors are especially suited to the use of SPR. As more species-specific critical values are identified, the use of SPR to evaluate and assess freshwater and marine fisheries should increase.

11. USING FAST's SPREADSHEET AND GRAPHICS MODULES

Spreadsheet Module

The spreadsheet module embedded within FAST is provided primarily as a tool for inputting data and displaying output data and results from a model run. However, the spreadsheet module can also function as a stand-alone spreadsheet providing functions similar to those found in other spreadsheet packages - saving, opening, copying, pasting, sorting, summing, etc. Since the spreadsheet module is embedded within FAST as an add-in program, its functions are not accessible until the user activates the spreadsheet. This is done simply by choosing **Activate Spreadsheet** under the **Spreadsheet** menu. Although data can be entered into the spreadsheet while in its embedded form, the spreadsheet must be activated in order to perform all other spreadsheet functions. Alternatively, all FAST functions that require data contained within a spreadsheet can only be performed while the spreadsheet is in its embedded form. To return to the embedded form of the spreadsheet from the active form, simply close the active spreadsheet.

Data can be written to and read from files of the following types: Formula one (*.vts), Excel 4 or 5 (*.xls), or tab-delimited text (*.txt). The spreadsheet module is compatible with Microsoft Excel® version 5 or earlier, therefore, any data created in Excel that the user wishes to use in FAST should either be pasted into a FAST spreadsheet or saved as an older version of Excel then read into a FAST spreadsheet. When reading Excel data into FAST, Excel 4 should be used rather than Excel 5. The reason for this is that when FAST performs computations on the data contained in a spreadsheet, it looks for the data in a specific sheet (the first sheet from the right) and Excel 5.0 files, when opened in FAST, have the data placed in the first sheet from the left. Since Excel 4 files do not contain multiple sheets, when they are opened in FAST the data will always be located in the proper sheet. Alternatively, when saving a FAST spreadsheet as an Excel file, Excel 5 should be used if the FAST output contains multiple sheets, as saving to Excel 4 will save only the active sheet. If Excel compatibility is not required, saving input and output data is best accomplished using the default (*.vts) format.

When conducting analyses such as catch-curves, weight-length regressions, etc., data must be properly entered into the first sheet of the spreadsheet. Not only does FAST look for input data in a specific sheet, it looks for data in specific columns and rows. The first row must contain column headers as text, with the associated numerical data entered in the rows beneath the header row. Example input data files are provided for each analysis FAST performs so the user can see how data should be entered.

Graphics Module

Since each model run can generate thousands of lines of output, a graphical representation of the data is necessary for any type of interpretation. FAST incorporates an embedded add-in graphics program to display the results of a model run in a graphical form. Although the plots produced by FAST are not intended to be publication quality, they are more than adequate for interpretation and presentation.

Once produced, FAST plots can be edited, saved, and printed. Plots can be saved as a number of different image formats including bitmap (*.bmp), JPEG (*.jpg), and Windows metafile (*wmf). Once saved as one of these formats, the plot can then be inserted as an object into a presentation software package such as Microsoft PowerPoint®.

Virtually any property of a FAST plot can be edited by accessing the plot's chart control. This is accomplished by choosing **Chart Elements** under the **Edit** menu of the plot window. The chart control properties window allows the user to edit chart properties such as coloring, borders, titles, legends, symbol size, etc. Also, an extensive help file is available through the chart control properties window to aid the analyst in editing the chart properties.

12. REFERENCES

Allen, M. S., and L. E. Miranda. 1995. An evaluation of the value of harvest restrictions in managing crappie fisheries. North American Journal of Fisheries Management 15:776-772.

Allen, M. S., and W. E. Pine, III. 2000. Detecting fish-population responses to a minimum length limit: Effects of variable recruitment and duration of evaluation. North American Journal of Fisheries Management (submitted).

Anderson, R. O., and R. M. Neumann. 1996. Length, weight, and associated structural indices. Pages 447-482 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques. 2nd edition. American Fisheries Society, Bethesda, Maryland.

Beamesderfer, R. C. 1991. MOCPOP 2.0: a flexible system for simulation of age-structure populations and stock-related functions. Oregon Department of Fish and Wildlife Information Report 91-4.

Beamish, R. J., and G. A. McFarlane. 1987. Current trends in age determination methodology. Pages 15-42 *in* R. C. Summerfelt and G. E. Hall, editors. Age and Growth of Fish. Iowa State University Press, Ames, Iowa.

Berlinsky, D. L., M. C. Fabrizio, J. F. O'Brien, and J. L. Specker. 1995. Age-at-maturity estimates for Atlantic coast female striped bass. Transactions of the American Fisheries Society 124:207-215.

Bettoli, P. W., M. J. Maceina, R. L. Noble, and R. K. Betsill. 1992. Piscivory in largemouth bass as a function of aquatic vegetation abundance. North American Journal of Fisheries Management 12:509-516.

Beverton, R. J. H., and S. J. Holt. 1957. On the dynamics of exploited fish populations. Chapman and Hall, London.

Beverton, R. J. H., and S. J. Holt. 1959. A review of the life spans and mortality rates of fish in nature, and their relationship to growth and other physiological characteristics. CIBA Foundation Colloquia on Ageing 5:142-180.

Chen, S. and S. Watanabe. 1989. Age dependence and natural mortality coefficient in fish population dynamics. Nippon Suisan Gakkaishi 55:205-208.

Cushing, D. H. 1968. Fisheries biology: a study in population dynamics. University of Wisconsin Press, Madison.

Cushing, D. H. 1974. The possible density-dependence of larval mortality and adult mortality in fishes. pages 103-111 *in* J. H. S. Blaxter, editor. The early life history of fish. Springer-Verlag, New York, New York.

Dorazio, R. M., K. A. Hattala, C. B. McCollough, and J. E. Skjeveland. 1994. Tag recovery estimates of migration of striped bass from spawning areas of the Chesapeake Bay. Transactions of the American Fisheries Society 123:950-963.

Ferson, S., and H. R. Akcakaya. 1988. RAMAS/age user manual: modeling fluctuations in age-structured populations. Exeter Software, Setauket, New York.

Field, J. D. 1997. Atlantic striped bass management: where did we go right? Fisheries 22(7):6-8.

Fruend, R. J., and R. C. Littell. 1991. SAS system for regression. SAS Institute, Cary, North Carolina.

Goodyear, C. P., and S. W. Christensen. 1984. On the ability to detect the influence of spawning stock on recruitment. North American Journal of Fisheries Management 4:186-193.

Goodyear, C. P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. Pages 67-71 *in* S. J. Smith, J. J. Hunt, and D. Rivard, editors. Risk evaluation and biological reference points for fisheries management. Canadian Journal of Fisheries and Aquatic Sciences, Special Publication 120.

Guy, C. S. and D. M. Willis. 1995. Population characteristics of black crappie in South Dakota waters: a case for ecosystem specific management. North American Journal of Fisheries Management 15:754-765.

Hansen, M. J., M. A. Bozek, J. R. Newby, S. P. Newman, and M. D. Staggs. 1998. Factors affecting recruitment of walleyes in Escanaba Lake, Wisconsin, 1958-1996. North American Journal of Fisheries Management 18:764-774.

Hillborn, R., and C. J. Waters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82:898-903.

Jensen, A. L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Canadian Journal of Fisheries and Aquatic Sciences 53:820-822.

Johnson, B. L. 1995. Applying computer simulation models as learning tools in fishery management. North American Journal of Fisheries Management 15:736-747.

Johnson, B. M., and P. J. Martinez. 1995. Selecting harvest regulations for recreational fisheries: Opportunities for research/management cooperation. Fisheries 20(10):22-29.

Jones. R. 1957. A much simplified version of the full yield equation. International Commission for Northwest Atlantic Fisheries, International Council for the Exploration of the Sea, and Food and Agricultural Organization of the United Nations, Document P.21, Lisbon.

Keefer, L. C., and H. L. Wilson. 1995. Differences in estimates generated by two tag types. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies (1993) 47:611-621.

Larson, S. ., B. Saul, and S. Schleiger. 1991. Exploitation and survival of black crappies in Georgia reservoirs. North American Journal of Fisheries Management 11:604-613.

Lewis, R. M., and R. R. Bonner, Jr. 1966. Fecundity of the striped bass, *Roccus saxatilis* (Walbaum). Transactions of the American Fisheries Society 95:328-331.

Mace, P. M., and M. P. Sissenwine. 1993. How much spawning per recruit is enough? Canadian Special Publication on Fisheries and Aquatic Sciences 120:101-118.

Maceina, M. J., P. W. Bettoli, and D. R. DeVries. 1994. Use of a split-plot analysis of variance design for repeated-measures fishery data. Fisheries 19(3):14-20.

Maceina, M. J. 1997. Simple application of using residuals from catch-curve regressions to assess year-class strength in fish. Fisheries Research 32:115-121.

Maceina, M. J., P. W. Bettoli, S. D. Finely, and V. J. DiCenzo. 1998a. Analyses of the sauger fishery with simulated effects of a minimum size limit in the Tennessee River of Alabama. North American Journal of Fisheries Management 18:66-75.

Maceina, M. J., O. Ozen, M. S. Allen, and S. M. Smith. 1998b. Use of equilibrium yield modeling to evaluate length limits for crappie in Weiss Lake, Alabama. North American Journal of Fisheries Management 18:854-863.

Maceina, M. J., and R. K. Betsill. 1987. Verification and use of whole otoliths to age white crappie. Pages 267-278 *in* R. C. Summerfelt and G. E. Hall, editors. Age and Growth of Fish. Iowa State University Press, Ames, Iowa.

Maceina, M. J., and J. W. Slipke. (in preparation). Use of catch-curves regressions to predict age-1 recruitment variability in fish.

Maceina, M. J., and M. R. Stimpert. 1998. Relations between reservoir hydrology and crappie recruitment in Alabama. North American Journal of Fisheries Management 18:104-113.

Mansueti, R. J. 1961. Age, growth, and movements of the striped bass, *Roccus saxatilis*, taken in size selective fishing gear in Maryland. Chesapeake Science 2:9-36.

Merriman , D. 1941. Studies on the striped bass (*Roccus saxatilis*) of the Atlantic coast. Fishery Bulletin 50:1-77.

Montgomery, D. C., and E. A. Peck. 1982. Introduction to linear regression analysis. John Wiley & Sons, New York.

Noble, R. L. 1981. Management of forage fishes in impoundments of the southern United States. Transactions of the American Fisheries Society 110:738-750.

Ozen, O. 1997. Crappie population characteristics in six Alabama reservoirs. Master thesis, Auburn University, Alabama.

Parkes, G. 2001. Understanding SPR and its use in U.S. fisheries management. Report of MRAG Americas, Inc. to The Ocean Conservancy, Washington, D.C.

Pauly, D. 1980. On the interrelationship between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal du Conseil International pour l'Exploration de la Mer 39:175-192.

Peterson, I, and J. S. Wroblewski. 1984. Mortality rate of fishes in the pelagic ecosystem.. Canadian Journal of Fisheries and Aquatic Sciences 41:1117-1120.

Pitlo. J. Jr. 1997. Response of upper Mississippi River channel catfish populations to changes in commercial harvest regulations. North American Journal of Fisheries Management 17:848-859.

Prager, M. H., S. B. Saila, and C. W. Recksiek. 1989. FISHPARM: a microcomputer program for parameter estimation of nonlinear models in fishery science. Technical Report 87-10, Department of Oceanography, Old Dominion University, Norfolk, Virginia.

Quinn, T. J., II, and R. B. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, New York.

Rice, J. A. 1999. Coping with uncertainty. Fisheries 24(2):4.

Richards, R. A., and P. J. Rago. 1999. A case history of effective fishery management: Chesapeake Bay striped bass. North American Journal of Fisheries Management 19:356-375.

Ricker, W. E. 1975. Computation and interpretation of biological statistics in fish populations. Fisheries Research Board of Canada Bulletin 191.

Rieman, B. E., and R. C. Beamesderfer. 1990. White sturgeon in the lower Columbia River: Is the stock overexploited? North American Journal of Fisheries Management 10:388-396.

Sammons, S. M, and P. W. Bettoli. 1998. Larval sampling as a fisheries management tool: Early detection of year-class strength. North American Journal of Fisheries Management 18:137-143.

SAS. 1988. SAS/STAT user's guide 6.03 edition. SAS Institute, Cary, North Carolina.

Shepard, S. A., and P. A. Breen. 1992. Mortality in abalone: its estimation, variability, and causes. Pages 276-304 *in* S. A. Shepard, M. J. Tegner, and S. A Guzman del Proo, editiors. Abalone of the World: Biology, Fisheries, and Culture. Fishing New Books, Cambridge, United Kingdom.

Slipke, J. W., M. J. Maceina, V. H. Travnichek, and K. C. Weathers. 1998. Effects of a 356-mm minimum-length limit on the population characteristics and sport fishery of smallmouth bass in the Shoals Reach of the Tennessee River, Alabama. North American Journal of Fisheries Management 18:76-84.

Starfield, A. M., and A. L. Bleloch. 1986. Building models for conservation and wildlife management. Macmillan, New York.

Steel, R. G. D., and J. H. Torrie 1980. Principles and procedures of statistics: A biomettrical approach. 2nd edition. McGraw-Hill, New York.

Taylor, C. J. 1981. A generalized inland fishery simulator for management biologists. North American Journal of Fisheries Management 1:60-72.

Urshin, E. 1967. A mathematical model of some aspects of fish growth, respiration, and mortality. Journal of the Fisheries Research Board of Canada 24:2355-2453.

von Bertalanffy, L. 1938. A quantitative theory of organic growth. Human Biology 10:181-213.

Wilde, G. R. 1997. Largemouth bass fishery responses to length limits. Fisheries 22(6):14-23.

Wrenn, W. B., D. R. Lowery, M. J. Maceina, and W. C. Reeves. 1996. Largemouth bass and aquatic plant abundance in Guntersville Reservoir, Alabama. Pages 382-392 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional approaches to reservoir fisheries management. American Fisheries Society Symposium 16.

Wright, G. L. 1991. Results of a water level management plan on largemouth bass recruitment in Lake Eufaula, Oklahoma. Pages 126-130 *in* J. L. Cooper and R. H. Hamre, editors. Warmwater Streams Symposium. United States Forest Service, Washington DC.