Report on the Bioeconomic Modeling Workshop

July 23-25, 2002
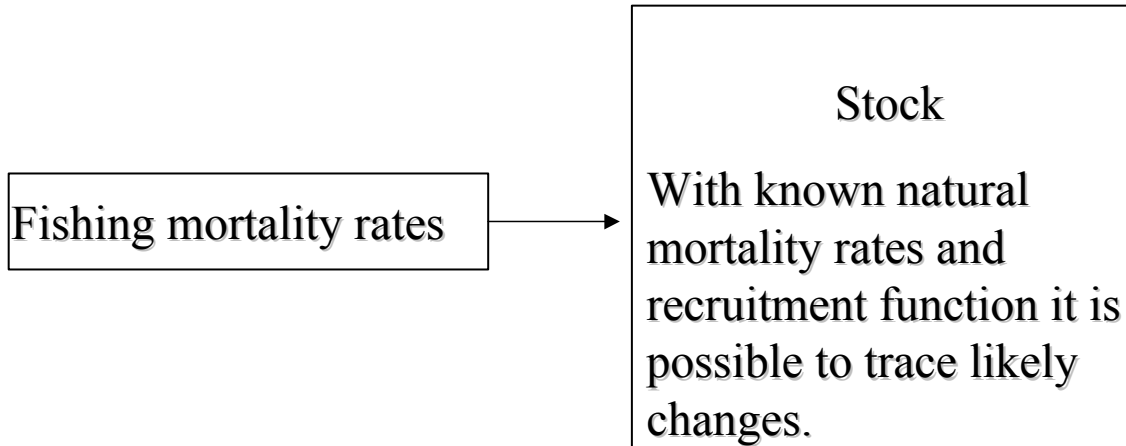
Lee G. Anderson

Introduction

On the basis of a recommendation of the ASMFC Committee on Economics and Social Sciences, a short workshop to discuss the potential for using bioeconomic models to improve the information provided to Commission members as they make management decisions was held July 23-25, 2002. The objective of the meeting was to collect biological and economic data on the striped bass fishery and apply it to a simulation model developed by Lee Anderson to provide a real world example of how to build a bioeconomic model and to demonstrate what kind of results are possible. See the draft proceedings of the meeting prepared by Joe Moran (Attachment 1). The simulation model was successfully calibrated to the biological information provided by John Carmichael.

However, it soon became apparent that because of a lack of some non-biological data, primarily WTP functions for recreational fishing, and because of the complexities of state by state management, it would not be possible to use stripers as a case study. Instead, the workshop participants created a hypothetical fishery based on the basics of the striper stock assessment. Using this second best option, a status quo exploitation pattern was developed under which the hypothetical fishery was pushed to and over-fished situation. Then the usefulness of bioeconomic modeling was demonstrated by comparing seven different regulatory schemes for rebuilding the spawning stock. A file containing summary graphs and a brief description of each scenario has been provided to the Commission. These are described in Attachment 1.

The purpose of this report is to: (1) provide more background on bioeconomic modeling in general and on the LEM model in particular; (2) explain in more detail the nature of the results that can be provided by using one of the scenarios as an example; and (3) describe steps that will have to be taken in order to use bioeconomic modeling as part of the management process. As the Commission considers the further use of bioeconomic modeling, the report can be used as background material for staff members preparing briefings on the subject and as a short summary to be provided to interested members of the Commission family.
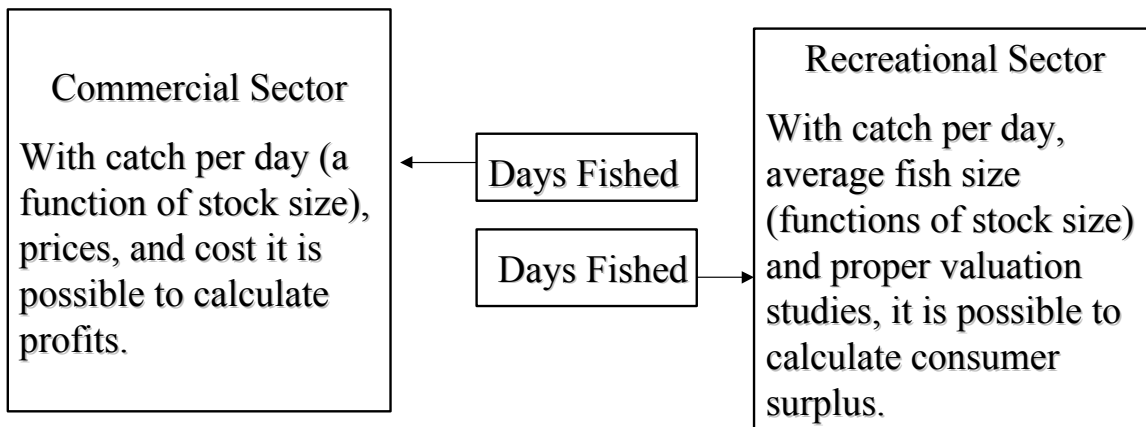
What is Bioeconomic Modeling?

Bioeconomic analysis combines biological and economic models to provide a more complete examination of fisheries utilization. Biological analysis can be used to predict the likely changes in stock, cohort sizes, SSB and landings that will result from given fishing mortality rates. This can be useful for decision making because it allows for a comparison of status quo and effects of a policy change.
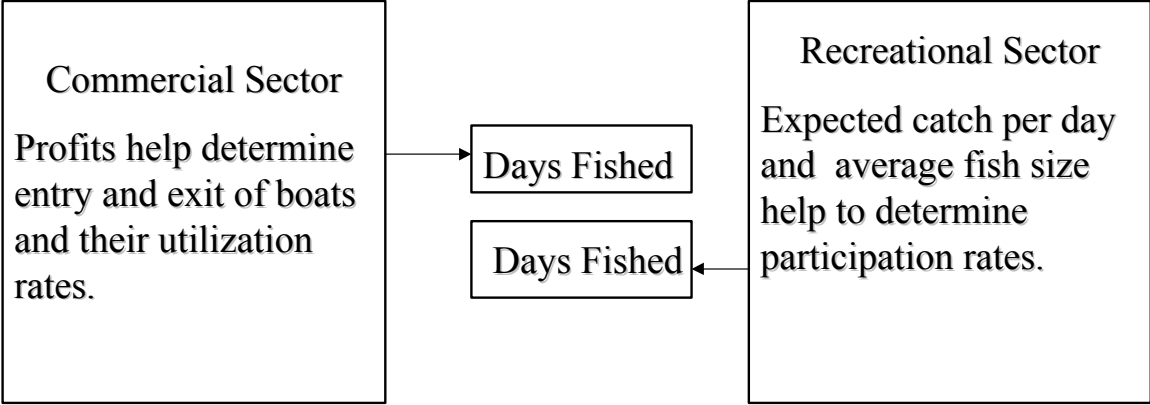
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┌─────────────────────────┐                    ┌──────────────────────────┐
│                         │                    │         Stock            │
│ Fishing mortality rates │ ─────────────────▶ │ With known natural       │
│                         │                    │ mortality rates and      │
└─────────────────────────┘                    │ recruitment function it  │
                                               │ is possible to trace     │
                                               │ likely changes.          │
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Biological Analysis

Economic analysis can used to predict the likely changes in "net returns" in terms of profits in the commercial sectors and consumer surplus in the recreational sector, that will result from given patterns of days fished.
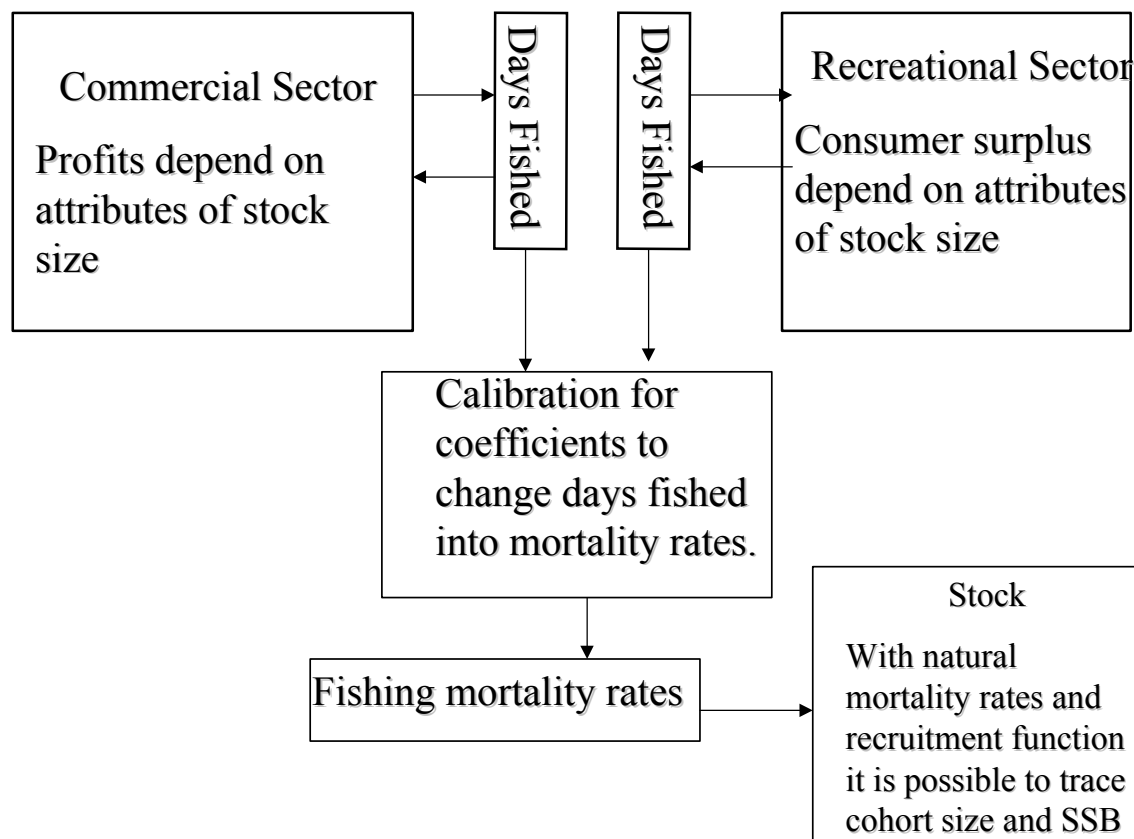
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┌─────────────────────────┐                    ┌──────────────────────────┐
│   Commercial Sector     │                    │    Recreational Sector   │
│                         │  ┌────────────┐     │ With catch per day,      │
│ With catch per day (a   │◀─│ Days Fished│     │ average fish size        │
│ function of stock size),│  └────────────┘     │ (functions of stock size)│
│ prices, and cost it is  │  ┌────────────┐     │ and proper valuation     │
│ possible to calculate   │  │ Days Fished│────▶│ studies, it is possible  │
│ profits.                │  └────────────┘     │ to calculate consumer    │
│                         │                     │ surplus.                 │
└─────────────────────────┘                     └──────────────────────────┘
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Economic Analysis I

Also, the logic of the analysis can be reversed to answer such questions as: How many days will be required to catch a specified amount of fish? How will changes in profits or consumer surplus change the number of fishing days?

| Commercial Sector

Profits help determine entry and exit of boats and their utilization rates. | | Recreational Sector

Expected catch per day and average fish size help to determine participation rates. |

Days Fished

Days Fished

Economic Analysis II

The two models can be combined by calibrating coefficients which transform fishing days into fishing mortality rates. By combining the two, a bioeconomic model allows for the study of how changes in stock size affect profits *and* how changes in fishing activity affect stock size.

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┌─────────────────────────┐  ┌──────┐ ┌──────┐  ┌─────────────────────────┐
│                         │  │      │ │      │  │                         │
│   Commercial Sector     │─▶│ Days │ │ Days │─▶│   Recreational Sector   │
│                         │  │Fished│ │Fished│  │                         │
│   Profits depend on     │◀─│      │ │      │◀─│  Consumer surplus       │
│   attributes of stock   │  │      │ │      │  │  depend on attributes   │
│   size                  │  │      │ │      │  │  of stock size          │
└─────────────────────────┘  └──────┘ └──────┘  └─────────────────────────┘
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Calibration for coefficients to change days fished into mortality rates.

Fishing mortality rates

Stock

With natural mortality rates and recruitment function it is possible to trace cohort size and SSB

Bioeconomic Analysis

Because of the ability to use days fished as the control variable, as opposed to fishing mortality rates, bioeconomic analysis is especially well suited to compare alternative management techniques designed to achieve the a desired fishing mortality pattern. That is, it can predict the likely fishing mortality pattern that will result from a particular alternative (closed season, trip limits, etc.) and at the same time predict the likely effects on participants.

The LEM Simulation Model.

The simulation models the joint commercial and recreational exploitation from an age structured fish stock where recruitment is a function of spawning stock stock. The data necessary to run the model include initial stock size and composition, the initial number of boats and recreational participants, the coefficients on the recruitment and individual growth equations, the age of sexual maturity, the catchability and natural mortality coefficients by cohort, values for prices and costs and the parameters of the marginal willingness to pay function for recreational participants. For a more complete description of the model, see Attachment #2.

Commercial Sector

Once the number of commercial and recreational fishing days produced by existing participants are converted to fishing mortality rates using the catchability coefficients, it is possible to calculate total harvest from a stock with a given age class distribution. Using standard formulas, the total harvest can then be divided into commercial and recreational catch. Given the

commercial harvest and the number of commercial fishing days, it is possible to calculate average harvest per fishing day, H_d. Vessel profits can be calculated as.

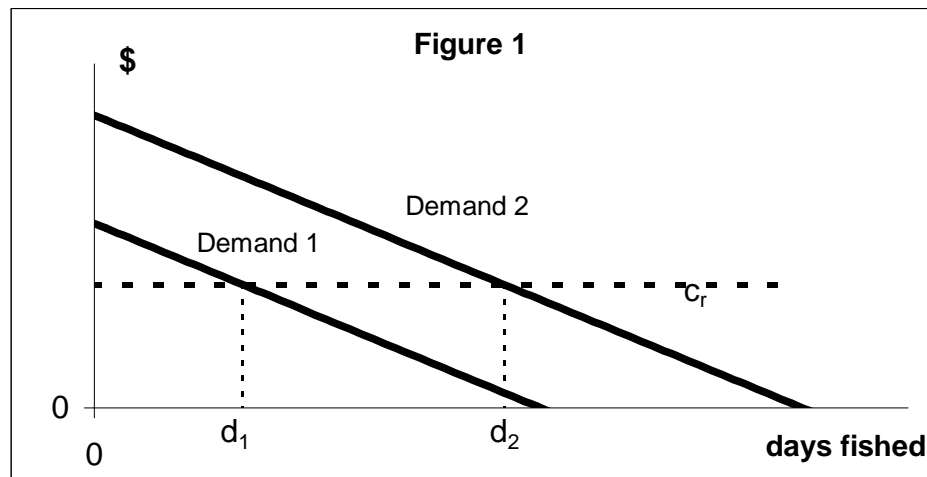$$\text{Vessel Profits} = P* H_d*D - C_d*D - FC$$

Where P equals price, D equals days fished, C_d equals cost per day, and FC equals fixed cost. It is usually fairly easy to obtain satisfactory estimates of these parameters.

Vessel profits will vary directly with stock size. They will also vary with the number of days fished if they are changed through regulations. Changes in the size of the fleet can be estimated using changes in profit.

Recreational sector

In order to capture the operation of the recreational sector in a way that is comparable to that of the commercial sector, it is necessary to find how participation rates vary with stock size and also to measure what use values are generated by a given level of participation. In the LEM model, recreational activity is modeled using a standard willingness to pay (WTP) approach. The marginal WTP for a day of recreational fishing for individuals is assumed to be a function of catch attributes and the number of days fished as follows.

$$WTP(i) = a_i CPD + b_i(creellimit) + c_i(Avwt) - slope_i * d_I$$

Figure 1

where CPD is catch per day in numbers, creellimit is a regulated limit on number of fish which can be landed per day, Avwt is the average weight of the catch and d_i is the number of days fished. When there is no regulated creellimit, it is assumed that all fish caught are landed and so the WTP is calculated setting creellimit equal to CPD. It is assumed that participants use the CPD and Avwt of the previous period in arriving at WTP in any given period.

6

Let cr_i be the cost of undertaking a recreational fishing day. The first three terms in the WTP equation will be a constant in any period and is the MaxWTP.

$$MaxWTP(i) = a_iCPD + b_i(creellimit) + c_i(Avwt)$$

Since participants will operate where marginal WTP is equal to cr_i, the number of days fished can be calculated as.

$$d_i = (MaxWTP(i) - cr\_i)/slope_i$$

Figure 1 depicts two recreational demand curves, each for a given stock size, and shows how the number of days fished is determined. As stock size increases, catch per unit of effort and average weight will increase which will shift the demand curve up. It will intersect the cost curve at a higher level, and the number of days fished will increase.

The calculated value d_i is the number of days that participants will want to fish in a given fishing season when there are no constraints on their behavior. However, if there is a recreational season length restriction, their behavior will be constrained. To account for this it is necessary to show how the desired number of fishing days is translated to actual fishing days given a recreational season length restriction. This is an important empirical question because it depends upon the amount of recoupment that occurs.

The value generated by recreational activity is measured by consumer surplus, which is the amount that participants would pay for the recreational fishing day over and above what they actually have to pay. The value is represented by the area below the demand curve but above the cost curve. It has proven difficult to find the necessary information to fully implement the recreational component of the model.

The Hypothetical Fishery

It was assumed that there were two fleets with the following characteristics.

	boats	trip cost	trips/year	days/trip
Fleet A	750	$ 195.00	30	1.00
Fleet B	1500	$ 60.00	30	1.00

It was also assumed that the catchability coefficient for fleet A is twice that for fleet B for all cohorts. For simplicity in running the model and explaining the results, it was assumed that the fleet sizes remain the same both with and without regulation. However, predicting changes in fleet size due to changes in profit is something than can and should be done in bioeconomic modeling.

It was assumed that there were 10,000 recreational participants and hypothetical numbers were used to specify their recreational demand curve. The actual values are not important except to note that they were set such that the participants valued catch per day far higher than landings per day. In other words, the participants were catch and release enthusiasts.

Simulation runs were made for seven different regulation programs. See Attachment 1 for a list of the regulatory schemes and a brief summary of the results. The actual results presented are not the important thing however because they depend upon the absolute and relative values of the economic and biological parameters used in the model. Those values can and will differ for other fisheries and, as a result, the effects of regulations will differ. The

purpose here is to show the types of information that can be provided using bioeconomic analysis.

To demonstrate this, the output of one of the scenarios will be presented and explained below. The output is set up to compare the difference between the status quo and the likely effects of the regulation.   The first set of graphs provides summary economic information on the net present value of current profits for both fleets and the net present value of consumer surplus to the recreational sector, both calculated for a 25 year time horizon using a 7% discount rate. They also show 25 year time plots of SSB and total stock biomass. The solid lines represent the predicted time paths given the status quo situation. The thin narrow horizontal line represents the SSB goal. As can be seen, the SSB will fall below the desired level.

The next set of graphs displays the time paths of important variables in the recreational and commercial sectors. Again the solid line represents the status quo time line. Landings in both sectors will fall. The short run profit per vessel, defined as the difference between revenue and variable costs per trip, will also fall significantly for both fleets. In the early years vessels from fleet A can cover fixed costs from activity in this fishery, but in later years in order to remain viable, it must obtain net revenue from other fisheries. Vessels in fleet B will always need to be active in other fisheries in order to cover costs.

It is important to note that the status quo is depicted as a time path rather than a point estimate for the current period. In order to implement appropriate management programs it is necessary to know where the system is moving, not just where it is currently located. At the same time it must be noted that while the simulation program makes estimates for long periods of time, the results must be interpreted with care.

Commercial	Status Quo	Change	
NPV Fleet a	$ 45,806,993	$98,431,664	115%
NPV Fleet b	$ 21,257,992	$83,231,461	292%
Total commercial	$ 67,064,985	$181,663,125	171%
Recreational			
NPV CS	$92,379,747	$122,528,470	33%
Grand Total	$159,444,732	$304,191,594	91%

Spawning Biomass x1000

Biomass Weightx1000
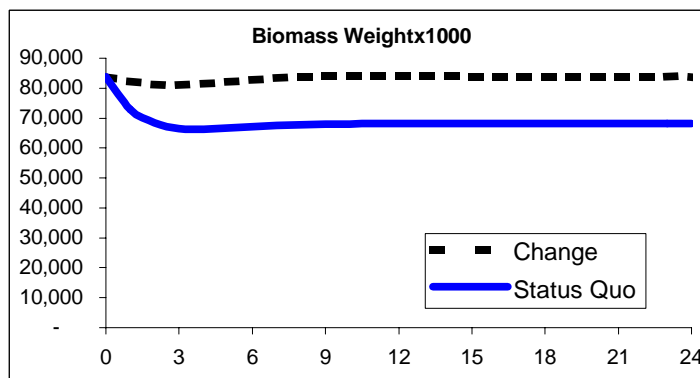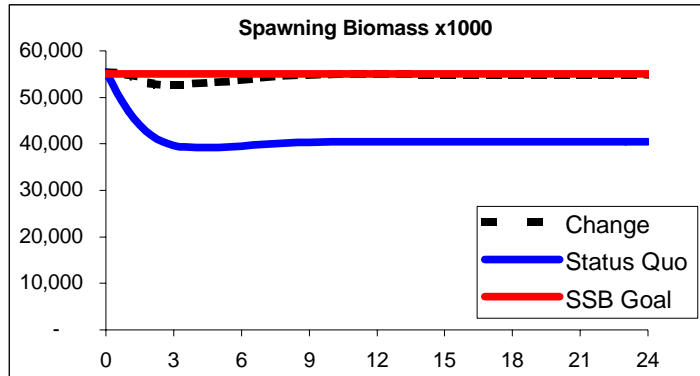
The management scenario depicted here is the result of the following question. How can we change the SSB time path such that the SSB goal is obtained in 10 years by implementing a closed season that applies to both the commercial and the recreational sectors. Using tools in the simulation program, it is a simple matter to find the allowable number of fishing days that will do this. See the dotted line in season length graph. The changes in the other variables that result from this season closure are shown as dotted lines in the other graphs.

Again while the particular numerical results can not be generalized, it is interesting to note that applying equal restrictions on the various participants does not affect them all in the same way. In the first place note that in this particular case what is good for the SSB is also good for economic returns in the long run. The NPV of current profit to both fleets and of consumer surplus to recreational participants will all increase under this management regime. Bioeconomic modeling allows for economic success or failure to be consider along with biological success or failure for any particular set of management measures. Further it can be used to rank different management programs which all met biological goals according to their economic effects. To return to the discussion, note that in this case although there are economic

gains, the percentage change to different participants is different. Fleet B has a higher percentage growth in NPV from the same change in stock biomass, because vessel costs are lower and there are more boats in the fleet.
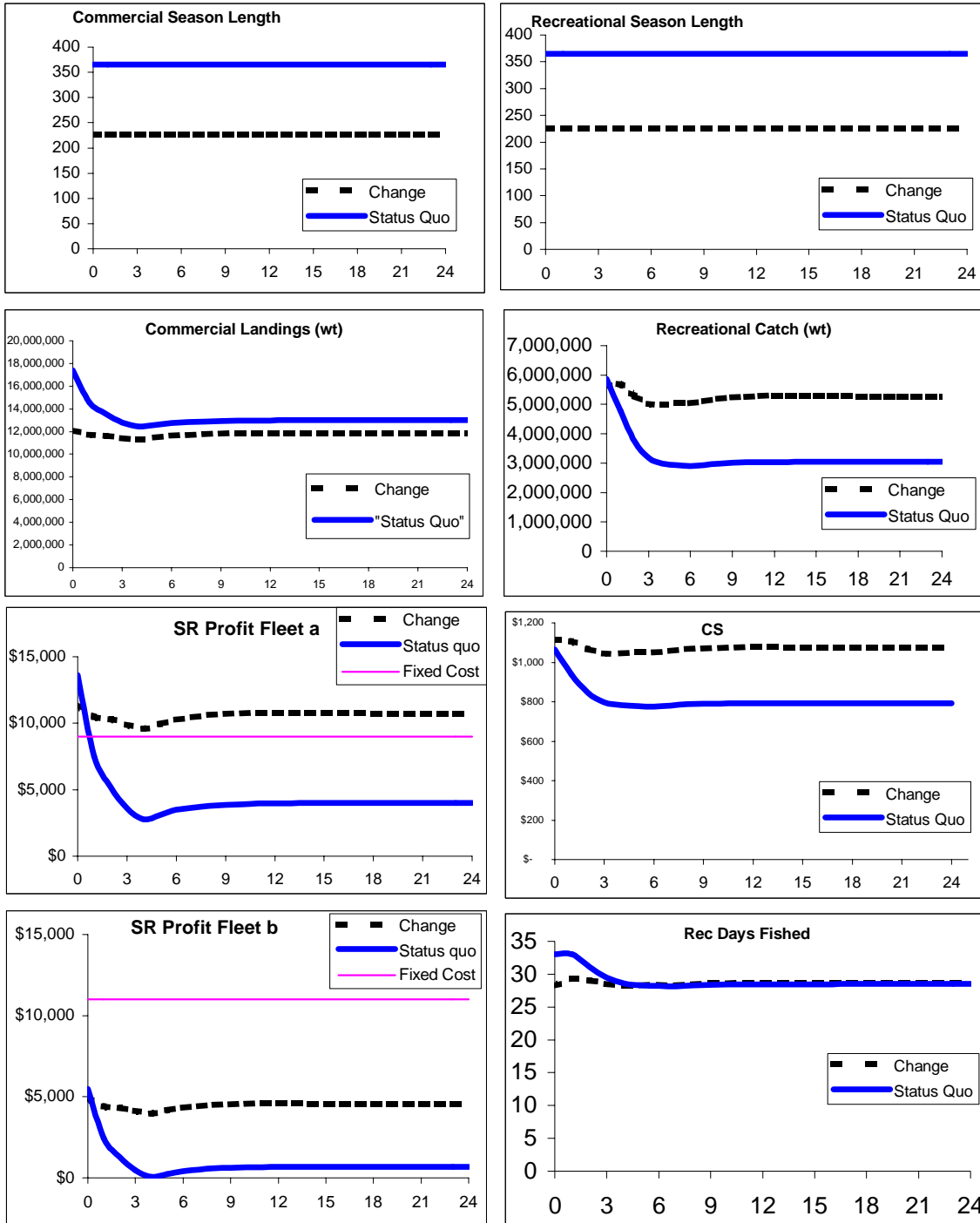
Note also that while commercial landing will be lower than the status quo level at all times, recreational catch will only be lower at the very beginning. This is because of the way recreational participants react to the combination of the season closure and the resultant increase in stock size. The first will tend to decrease the number of days fished, however the second will cause them to go up. Given the taste structure implicit in the willingness to pay function, the higher stock size will encourage people to fish more during the open season.

Before moving on to the next section, it is always wise to remember the limitations of modeling whether it is biological, economic or bioeconomic. As part of building a model, we must assume, among other things, that we have the correct functional relationships and they do not change over time, that there is no technological change and no change in prices and costs, that the parameters are estimated correctly, and that there are no stochaistic jolts to the system. As a result, the outputs of the models must be interpreted with care.

Necessary Steps to Towards the General Application of Bioeconomic Modeling

1. Improve the existing empirical work on recreational willingness to pay functions and on relationships between characteristics of the fishing activity (cpue, average length, average weight) and participation levels.
2. Increase cooperation between economists and biologists at all levels from stock assessment to model building.
3. Expand the management plan development process to include bioeconomic analysis. This will allow for models to be built that are capable of assessing the types of management regimes being considered and the biological and economic variables that are of interest to the mangers
4. Where necessary build multi-species and multi-fleet models to allow managers to see the effects that managing one fleet or species will have on others.
5. At the same time build disaggregated models which can handle the biological aspects of stock as one unit but can consider the effects of individual state management for such species as stripers and black sea bass.

Attachment 1
    Draft Proceedings

Attachment 2
    LEM User Guide

APPENDIX 1   Draft Proceedings

Bioeconomic Modeling Meeting

July 23-25, 2002   Washington, DC

Draft Proceedings[1]

A bioeconomic modeling session was held July 23/25, 2002, to provide insight on the integration of economic information into the stock assessment (hence, the fisheries management) process. Dr. Lee Anderson (U DE), Dr. John Ward (NMFS HQ), John Carmichael (NC DMF and Chairman of the ASMFC Striped Bass Technical Committee, Dr. Lisa Kline (ASMFC), Jeff Brust (ASMFC), Joe Moran (ASMFC), and Carlos Garcia-Quijano (U GA, ASMFC Summer Intern) participated in the meeting. A bioeconomic model (written in MS EXCEL) developed by Dr. Anderson was utilized. The same model had been used very recently by Dr. Anderson for the Gulf of Mexico Fisheries Management Council to examine bioeconomic ramifications of different management strategies related to the red grouper fishery.

Striped bass was used as the test species for this meeting. Required biological data was obtained from the stock assessment report and other sources, with additional data supplied by J. Carmichael. Season lengths, size limits, commercial and recreational landings, ex-vessel prices, and estimated numbers of commercial vessels and participants were obtained by state. Two commercial fleets (gill nets and hook & line) and a recreational participation component (MRFSS data, using total numbers of trips which targeted striped bass as a proxy) were added. Estimates of commercial and recreational trip and annual fixed costs were obtained from several industry contacts in the New England and Chesapeake Bay areas. All compiled information was forwarded to Dr. Anderson so the model could be calibrated in advance of the meeting.

Dr. Anderson provided an explanation of the model and the relationships between the input parameters. Participants discussed the model inputs, assumptions, and caveats. It was apparent that these types of exercises should not be undertaken without knowledgeable biological personnel in attendance. Discussions centered on the nuances of striped bass management and how those nuances could be handled within the model. Most biological information was known, as striped bass has been managed under an ASMFC fishery management plan for years. However, several model inputs were problematic due to the myriad of state-specific regulations (season lengths, bag/size limits, etc.) and the lack of definitive numbers of recreational and commercial participants/vessels. In addition, no economic demand function information was available.

Several iterations of the model were run using the available data. It soon became clear that due to a lack of some non-biological data and because of the complexities of state by state management, it would not be practical to use striped bass as an example to demonstrate the benefits of bioeconomic modeling. Instead the working group created a hypothetical fishery using the basics of the striper stock assessment model as the biological component.

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[1] Drafted August 8, 2002

As the purpose of the exercise was to provide an overview of the utility of bioeconomic models in the Commission's management process, the group believed that the benefits and requirements of bioeconomic modeling could be better depicted with the "generic fishery". General economic parameters were constructed and most striped bass biological information was retained. Two commercial fleets (each allocated ½ of the commercial catch) and a recreational component were input into the model. No cohort-specific discard mortalities were retained and discard total weights were added to the catch totals. The model was recalibrated based on the new "fishery".

The modeling session participants caution readers to remember that the following scenario outcomes were predicated on false data and should be considered as demonstrations of the types of outcomes and explanations possible as a result of model runs. It also should be noted that models only are used to provide advice to the fishery management process. They are tools to determine possible outcomes of different scenarios in advance of actual implementation of management strategies.

Scenario 1
This scenario represents the status quo, based on the striper SSR and 1999 age class distribution and hypothetical participants. There were two types of vessel/gear and a set of recreational participants. It was assumed that the vessels target other species during parts of the year (if the boats are to remain viable they must make enough from all fisheries to cover fixed costs). It was also assumed that prices (per pound) and the number of commercial and recreational participants do not change. The number of days fished by recreational participants will change with changes in stock size.

The status quo was set so that with no management action most measurable parameters deteriorated quickly. SSB, biomass, profits, and consumer surplus for recreational participants all fall. In this scenario, though the recreational sector only takes about 22% of the catch they produce more value. This is to show that a fish to one sector may not produce the same amount as a fish in another sector.

Scenario 2 – Model Predicted Graphs Included
This scenario was based on selecting a closed season for the commercial fishery to achieve an SSB goal. In this example, even though all of the regulation burden was placed on the commercial sector, they showed economic benefits in the long run. Short run profit falls below the status quo for the first few years, but soon would be above it. The boats would show improved profits because stock improvements would increase CPUEs such that the increased profit per day made up for the shorter season. The two commercial fleets were affected differently. The recreational sector benefited from the increased stock size.

Scenario 3
This scenario placed full management burden on the recreational fishery (the counterpart to Scenario 2). In this example however, even though the recreational fishery is completely shut down the SSB goal cannot be achieved. Gains to the commercial sector and losses to the recreational sector were noted.

Scenario 4
The scenario objective was to reach the SSB goal by placing equal season lengths on both commercial and recreational sectors. This example showed few differences than the unilaterally closed commercial season, because the recreational sector did not respond as rapidly as did the commercial sector. Even though there was a equal closed period, there were not equal effects on catch (recreational catch increases). The apparent inconsistency was the result of the increased catch per day (brought about by decreased commercial catch) which made up for the decrease in days fished. Because of recoupment, the number of recreational fishing days does not decrease linearly with the length of the closed season.

Scenario 5
In this scenario, identical size limits were placed on both sectors (neither can land individuals from the first five cohorts). Equal restrictions did not have equal results. The commercial sector was hurt badly because of the lost harvest per trip even after the stock recovered. The recreational sector was set up to have a hook and release mentality. They obtained satisfaction from catching the smaller fish even when they could not keep them. As a result of the size limit CPUEs increased, which means that over time the value of a fishing day increased.

The loss in net benefits (net present value…NPV) assumed that both commercial fleets continue to fish even with negative net profits. There would be a smaller loss, but a loss none the less, if some of the boats did exit the fishery. They will probably do so unless they remain for customary reasons or if they wanted to remain active to maintain a license.

Scenario 6
This scenario modeled possible outcomes of a one fish creel limit on the recreational sector and a two month closure in the commercial sector. The results are similar to the other cases.

Scenario 7
This scenario examined the results of a TAC that restricted harvest to 90% of what would have been taken under open access for the first ten years and then increased it to 110% of open access for the next 15 years. The TAC was distributed between recreational and commercial sectors in proportion to status quo catch. Again, the same policy (between recreational and commercial) had different effects. The commercial sector benefited in the long run. However, because of recoupment, it took a severe drop in days fished to achieve the desired restricted catch, especially as the stock size increased. Although each day is valuable because of the improved CPUEs, etc., total benefits will fall because of the drop in days fished.

Scenario 8
A different TAC path was modeled in this scenario and results indicated the initial reduction in harvest was not as severe as in the previous example. While the general results were the same with respect to comparative effects on the two sectors, in this case the recreational sector showed a small gain the NPV because of the higher initial CS. Again, as the stock grew, the number of recreational fishing days must be reduced significantly in order to maintain the TAC and CS will fall.

Benefits of Bioeconomic Modeling – "What can we do with these models?"
- Managers will have a tool to examine possible outcomes of many different fishery management strategies before actual implementation, or to fine-tune existing strategies.
- Examine costs associated with season lengths, bag limits, or size limits required to reach or maintain target SSBs.
- Examine potential outcomes of increases or decreases in fleet sizes (commercial and recreational).
- Examine potential profit to vessels over time as a result of different management strategies. Likewise, can examine costs of stock rebuilding (as a function of length of time required to reach targets).
- Examine possible results from catch allocation scenarios between gear types.
- Project levels of commercial/recreational harvest allocation as stock size increases over time.
- Show how F may change based on size limits, allowable catch, or other management strategies.
- Examine profitability to industry based on fixed F scenarios.
- Examine how individuals may change fishing behavior based on stock availability.

- Project numbers of days fishing required (commercial and recreational) to maintain harvest levels.
- Examine possible outcomes of recreational or commercial season closures (days fished).
- Models should help improve the prediction of certain biological parameters (rather than fixed constant F, economic parameters will help predict real-world fluctuations of F based on economic parameters).

Bioeconomic Modeling Requirements
- Model building MUST be interdisciplinary. At a minimum, biologists and economists must discuss caveats specific to the species/fishery at hand and both parties should be at the table when the model is run. Better would be collaboration between biologists and economists during the development of the model. These joint efforts help to focus future research requirements to make the models as robust as possible. Cost savings could result as a result of identification of identification of the future research requirements.
- Dependent on peculiarities of the species or fishery, coastwide modeling may not be optimal. These cases may require sub-area modeling.
- Data requirements include (may be required by state or region dependent on fishery/species):
  # of commercial vessels and days fished
  # recreational participants and days fished
  detailed effort parameters by trip (X fished 7 hrs with 10,000' net, Y fished 4 hrs with a 1000' net)
  accurate annual fixed cost and trip cost information from recreational and commercial sectors
  recreational and commercial economic demand function data must be available so the model may be as robust as possible.

<u>Future Activities</u>
- Additional species for which exists a broad base of biological information but few state-specific management strategies should be used in future exercises to further test the viability of these models (ex., menhaden, croaker).
- Advance planning may be required to allow recreational economic data to be collected under the MRFSS and analyzed by appropriate personnel (MRFSS may be able to provide certain economic data but the need must be identified well in advance of the actual sampling period to allow funding, question development time, sample draw, etc.).
- Consider formation of a steering committee to advance the use of modeling in the Commission's management structure. The group should consist of appropriate economic expertise, species technical committee personnel, and Advisory Panel members.

APPENDIX 2   **LEM Users Guide**

The LEM Fishery Simulation Model

Developed by

Lee G. Anderson

Excel Program Written by

Lee G. Anderson
Emiko Maruyama
Maryjane Middelkoop

Basics

The simulation models the joint commercial and recreational exploitation of a fish stock with 12 cohorts where recruitment is a function of spawning stock size in numbers. The basic parameters of the model are the initial stock size and composition, the initial number of boats and recreational participants, the coefficients on the recruitment and individual growth equations, the age of sexual maturity, the catchability and natural mortality coefficients by cohort, values for prices and costs and the parameters of the marginal willingness to pay function for recreational participants. These as well as the other parameters necessary to introduce regulation will be discussed below.

The model is capable of considering the effects of the following types of regulations.

- o commercial season length
- o recreational season length
- o commercial gear restrictions
- o commercial mesh restrictions
- o commercial size limits
- o recreational size limits
- o recreational creel limits
- o commercial limited days at sea programs
- o license limitations
- o commercial TAC
- o ("perfect") individual transferable quotas
- o commercial annual fishing mortality controls

Because fishing mortality is calculated using instantaneous equations and because it is tracked over the 12 cohorts separately, the simulation model is quite complex. Nevertheless, the basics can be introduced using the simplified flow diagrams in Figures 1 and 2. There are two harvesting sectors, a commercial fleet and recreational participants. There is only one commercial fleet but it is possible to designate two types of recreational participants. Both sectors produce fishing effort which imposes fishing mortality on the stock. The regulations listed above affect the amount of fishing effort that one of the sectors can produce in any year. In some cases, the regulations will be specific to the amount of fishing mortality that is imposed on specific cohorts. See the top half of Figure 1. The effort and the resultant fishing mortality produces harvest for the two sectors. The size of the commercial harvest determines vessel profits and vessels enter or exit the fleet depending on the size of current returns relative to fixed costs. The number of days fished by the recreational participants is a function of recreational harvest characteristics such as catch per day fished and average weight of fish caught.

With no fishing, the size of the fish stock depends upon the annual recruitment to the first cohort, and the natural mortality as the individual age through the 12 cohorts. Recruitment can be set as a constant or as a function of the size in numbers of the those cohorts which have achieved sexual maturity. Fishing will affect stock size and composition because of the additional mortality imposed on the various cohorts, and because of the effect on recruitment if fishing changes the size of the spawning biomass. Figure 2 depicts how the cohort size varies across time as a result of recruitment and natural and fishing mortality. Only the first three cohorts are included.

The following discussion describes the complete workings of the model in a step by step process giving emphasis to the theoretical issues involved. The worksheet entitled Glossary provides a formal definition of all of the parameters used in the model with references to the appropriate section of the following discussion. Note that typing the parameter name in the name box and then pushing the enter key will move the cursor to the parameter's location in the worksheet.

Stock Recruitment Function

Annual recruitment can either be set as a constant or as a function of the spawning stock size in numbers. In order to set a constant recruitment, type yes in cell D8 on Data worksheet and type the constant recruitment number in cell D7. If anything other than the word yes in inserted in cell D8, the stock recruitment function will apply.

The stock recruitment function is

$$R = R_{max}(1-e^{-\alpha(spawningstock-minspawningstock)})^3$$

Recruitment and spawning stock size are measured in numbers of fish. R_{max}, α, and, minspawningstock are parameters which can be set by the user. See Data worksheet cells D4, D5, and D6. Minspawningstock is the minimum stock size at which there will be recruitment. It can be set to zero. The spawning stock can consist of any combination of the 12 cohorts. This is determined by placing a zero (not included) or 1 (included) in rows 16 to 27 in column L of the Data worksheet.

To complete the basic population dynamics of the fish stock, it is necessary to set the instantaneous natural mortality of each cohort. This is done in Column G, Rows 16-27 of the Data Worksheet.

The workings of the population dynamics are described on the worksheet entitled Popdy. The graph at the top of the worksheet shows the recruitment sustainable spawning stock size in numbers that will be generated by any given spawning stock size. This is the stock size that results if recruitment is always equal to the amount generated by that stock size and the size of each cohort is determined by natural mortality. That is, the size of the ith cohort is equal to annual recruitment decreased by annual mortality occurring over i years. The stock size will be in equilibrium where the curve intersects the 45° line. Given the nature of the recruitment function, this will occur at two stock sizes. The smaller is an unstable equilibrium, because if stock size is above that level, stock size will grow and if stock size is below it, stock size will fall. The larger stock is stable and will be the non-exploitation equilibrium stock size, hereafter called the virgin stock size. This is analogous to the stock carrying capacity, K, in the Schaefer model. In the range over which the curve is higher than the 45° line, the fish stock can produce a sustainable harvest, because in the absence of fishing the spawning stock generated will be larger than the initial spawning stock. The length of this range is critical to the stability of the exploited fishery, because if fishing pushed the stock below the range, the stock can not survive.

The size and cohort distribution of the initial stock is critical to the operation of the fishery. One useful way to make comparisons is to start with the virgin spawning biomass. Other ways to set the initial stock size will be discussed below in the section called Model Calibration. To set the initial stock size equal to the virgin biomass, do the following.

1. Choose between constant recruitment or a stock recruitment function by placing yes or no in Cell D8 on the Data Worksheet.

2. Place yes in Cell C15 on the Data Worksheet, and make sure the word no is in Cells C20 and C27 on the Data worksheet. This simply organizes the initial cohort distribution toward the virgin biomass. The other choices are the bioeconomic equilibrium stock and a "choose your own" where the user selects the sizes of the initial cohorts.

3. Go to the Worksheet entitled Popdy and insert the value found in Cell A48 in Cell A49. Then, while remaining on the same worksheet, run the Macro entitled Virginstocksize. This is done by clicking on the Tools button, selecting Macros, and then selecting the Macro entitled Virginstocksize. This macro uses the goal seek tool to find the spawning stock size that will generate a recruitment sustainable spawning stock size equal to itself. Goal seek uses an iterative process to find this value, and it is necessary to place a relatively large number in Cell A49 to insure that the larger of the two equilibrium stock sizes in found.

The value for the virgin stock is shown in Cell J6 on the Popdy worksheet. By inspection, the user can determine if it corresponds to the larger of the two equilibria in the figure. If the word ok is not underneath the value, it means that the macro has not be run.

Following these steps will set the initial sizes of the cohorts such that they are in accord with the virgin biomass with no fishing.

Fishing Mortality and Harvest Levels

The change in the size of the ith cohort for a given period is

$$N_{i,final} = N_{i,intial} * e^{-(Fc+Fr+M)t}$$

Equation 1

where F_c is the instantaneous (daily) commercial fishing mortality, F_r is the instantaneous (daily) recreational fishing mortality, and M is the instantaneous (daily) natural mortality, and t is the number of "days" in a period[2]. The default for t is "NormT" which is set by the user in Cell B3 on the regulation worksheet. It will change under some regulations. The fishing mortalities are functions of the number of units operating per day and the instantaneous catchability coefficients. The natural mortality rates and the catchability coefficients for the 12 cohorts are specified in rows 16 to 27 and columns G to J in the Data worksheet. (There are actually two types of recreational fishers.) Setting a catchability coefficient to zero will mean that cohort is not vulnerable to fishing.

The harvest of the two sectors for any cohort is calculated as follows:

$$Hc(i) = F_c(i)/(F_c(i)+F_r(i)+M)*(N_{i,intial} - N_{i,final})$$

$$Hr(i) = F_r(i)/(F_c(i)+F_{r(i)}+M)*(N_{i,intial} - N_{i,final})$$

The total catch in numbers is the sum of the harvest for all cohorts. Harvest is also translated into weight. See below.

The final size of a cohort in one period becomes the initial size the next cohort in the next period. That is

$$N_{i,final}(t) = N_{i+1,intial}(t+1)$$

Age-Weight Relationship

The age weight relationship is the standard von Bertalanffy equation. Weight is measured in kilograms.

$$W(t) = W_{infin}*(1-e^{-k(t-to)})^3$$

W_{infin} is the maximum weight a fish can obtain and k is the curvature parameter of the growth curve. As k increases, the number of years necessary to grow to the maximum weight decreases. The parameter t_o can be used to start fish growth at an age higher than zero. The parameters for the von Bertalanffy equation are set in column B, rows 5-7 of the Data worksheet. The weight at age (i.e., the average weight of a fish in the various cohorts) is calculated in column F, rows 16 to 27 of the Data worksheet. These figures are used when calculating the biomass of the stock and to measure the weight of the total harvest.

The Commercial Fishery

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[2] The values for F_c and F_r for the various cohorts are calculated starting at row 15 on the worksheet entitled Catchability Coefficients. The exact equations will be discussed below as the effects of various regulations are explained.

The commercial fleet is composed of identical vessels which enter and exit according to profit levels. There is an annual fixed cost (F_c) and a daily operating cost (C_d) which can be set in cells H5 and H6 on the Data worksheet. The total cost per period for an individual vessel is therefore

$$\text{Total Vessel Cost} = F_c + C_d*\text{Op\_T\_Com}$$

where Op_T_Com is the operational season length for the commercial fishery. Op_T_Com equals the normal season length (NormT) when there are no regulations but it changes when there is a commercial season length or a TAC. NormT is set in cell B3 on the Regulation worksheet.

The calculation of commercial harvest in numbers per cohort is described above and it depends upon F_c, the commercial fishing mortality coefficient, and the season length. See equation 1. The general equation for calculating these coefficients for each of the cohorts is:

$$\textbf{F}_\textbf{c}\textbf{(i) = (qc}_\textbf{i}\textbf{-decay*boats)*boats} \qquad \text{Equation 2}$$

The actual formula in the catchability coefficient worksheet is more complicated to allow for the effects of various regulations. This will be explained below. The parameter qc_i is the instantaneous commercial vessel catchability coefficient for the ith cohort. These are set in Column H, rows 16-27 on the data worksheet. Setting them to zero means that a cohort is not subject to commercial harvest. Boats is the number of commercial boats operating. The term decay*boats is included to allow for the possibility of crowding externalities in commercial harvest. That is, the vessel catchability coefficient decreases with increases in fleet size. The decay parameter is set in cell H3 in the data worksheet. It must be set with care or it is possible to have a negative commercial catchability coefficient. The t used in calculating equation 1 is Op_T_ Com as defined above.

Let Hcwt(i) be the commercial harvest from the ith cohort in weight. Periodic industry gross revenue (returns above variable costs) is calculated as

$$IGR = \Sigma P(i)*Hcwt(i)-(Boats*Op\_T\_com*Cd)$$

where all the parameters are as defined above and P(i) is the price per kilogram of the harvest from the ith cohort. The prices are set in cells K16-K27 on the Data worksheet. Periodic industry net revenue, (returns minus all costs) is calculated as

$$INR = IGR-(Boats*Fc)$$

There is entry or exit to the fleet according to size of IGR and INR. The change in fleet size is calculated as follows.

$$\Delta \text{fleet size} = mu_1*INR +(\text{if } IGR<0)mu_2*IGR$$

where mu_1 and mu_2 are positive entry/exit coefficients which are set in cells H7 and H8 of the data worksheet. This says that the fleet will increase if returns above all costs are positive and it will decrease if returns above all costs are negative. It also says that exit will be faster if returns above variable cost are negative. The initial fleet size is set in cell H2 of the data worksheet. To analyze a recreational only fishery, the initial fleet size and the entry/exit coefficients should be set to zero.

The Recreational Fishery

The model is set up to allow for two "groups" of recreational fishers. This allows for the possibility of considering different types of recreational participants. For example, the parameters explained below can be set up to have a group which primarily goes to put fish on the table and another group which is more concerned with number and size of fish caught but not so much with actual catch. It is assumed that the number of participants in each group is constant, but that the number of days fished will vary with stock conditions (and can go to zero). The number in each group is set in cells K3 and M3 on the data worksheet. To analyze a commercial only fishery, both should be set to zero, and to analyze a case where there is only one type of recreational fishery, one should be set to zero. The coefficients for the WTP functions and the cost per recreational fishing day for the two groups, described below, are set in cells K4-K8 and M4-M8 on the data worksheet.

Recreational activity is modeled using a standard willingness to pay (WTP) approach. The marginal WTP for a day of recreational fishing for individuals in either group is assumed to be a function of catch attributes and the number of days fished as follows.

$$WTP(i) = a_iCPD + b_i(creellimit) + c_i(Avwt) - slope_i*d_i$$

where CPD is catch per day in numbers, creellimit is a regulated limit on number of fish which can be landed per day, Avwt is the average weight of the catch and d_i is the number of days fished. When there is no regulated creellimit, it is assumed that all fish caught are landed and so the WTP is calculated setting creellimit equal to CPD. It is assumed that participants use the CPD and Avwt of the previous period in arriving at WTP in any given period. This means that WTP can not be determined in the initial period, and so the number of days fished can not be determined for that period either. It is arbitrarily set at 2 but this does not have any long run implications for model runs.

Let cr_i be the cost of undertaking a recreational fishing day for participants in group i. The first three terms in the WTP equation will be a constant in any period and is the MaxWTP for individuals in group i.

$$MaxWTP(i) = a_iCPD + b_i(creellimit) + c_i(Avwt)$$

Since participants will operate where WTP is equal to cr_i, the number of days fished can be calculated as[3] :

$$d_i = (MaxWTP(i) - cr\_i)/slope_i$$

If the calculated value of d_i is negative, it is set to zero and if the calculated value is greater than NormT, it is set to NormT. Figure 3 depicts a marginal willingness to pay curve and shows how the number of days fished is determined.

The calculated value d_i is the number of days that participants in group i will want to fish in a given fishing season when there are no constraints on their behavior. However, if there is a recreational season length restriction, their behavior will be constrained. To account for this it is necessary to show how the desired number of fishing days is translated to actual fishing days given a recreational season length restriction. This is done using the following equation:

$$d_i' = d_i*(Tr/NormT + Tr/NormT*(1-Tr/NormT))$$

As explained below, T_r is the regulated recreational season length and to be operational it must be less than NormT. The term in the parentheses will equal zero when T_r = zero and it equals 1 when T_r equals NormT. The number of fishing days will decrease with the ratio of T_r/NormT but the decrease will not be linear. If the calculated value of d_i' is greater than Tr, it is set equal to Tr.

If $N_r(i)$ is the number of participants in the ith group, then the total number of recreational fishing days for that group is $N_r(i)*d_i'$. It is assumed that these days are spread evenly over the season, so the number of recreational units operating on any day throughout the season is

$$RecE\_i = (N_r(i)*d_i')/T_r$$

The value for instantaneous recreational fishing mortality for group i for cohort j in equation 1 can be calculated as follows"

$$F_{ri}(j) = RecE\_i*qrj\_Reci$$

where qrj_Reci is the instantaneous catchability coefficient for the jth cohort for the ith group. These catchability coefficients can be set in columns I and J, rows 16-27 in the data worksheet.

The catch per cohort in numbers per group can be calculated using the above formulae. It is also possible to get total recreational catch in weight by converting numbers to weight and adding over cohorts and groups. Using the WTP functions for the two groups, it is a simple matter to calculate the CS for the two groups using the calculated days fished per season.

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[3] In some cases, it is possible to obtain a function for days fished as follows:

$$d_i = \gamma_{1i}CPD + \gamma_{2i} \text{ creellimit} + \gamma_{3i}Avwt - \gamma_{4i}cr\_i$$

These results can be translated into the WTP formulation used here as follows
$\gamma_{1i} = a_i/slope_i$, $\gamma_{2i} = b_i/slope_i$, $\gamma_{3i} = c_i/slope_i$, and $\gamma_{4i} = -1/slope_i$

Regulations

Commercial and recreational season length.

   The season for the recreation or the commercial fishery can be set to be less than NormT. The season length in days for the two fisheries, T_c and T_r, can be set at cells B4 and B5 on the regulation worksheet. If there is to be no season length these values must be set the same as NormT. It is assumed that the open season for either fishery will start at the beginning of the period. For example if NormT is 50, and T_c is 22, and T_r is 35, then both fisheries will operate for the first 22 days of the period, the recreational fishery will also operate from day 23 to day 35, and there will be no fishing from day 36 to day 50. For computational reasons, it is not possible to have the open season be in the middle or at the end of the period.

   For purposes of calculation, each period is divided into three periods in order to handle the different season lengths. Using the above numbers as an example, equation 1 would be used to show the change in each cohort size for the first 22 days and the numbers caught in each sector are recorded. The change in cohort size from days 23 to 35 is measured using equation 1 where F_c is set equal to zero and t is set equal to 13. The numbers caught in the recreational sector over that period are recorded. Finally the change is stock size from days 36 to 50 is measured using equation 1 with both F_c and F_r set equal to zero and t set equal to 15.[4]

Commercial gear restrictions

   Commercial gear restrictions are introduced by reducing the cohort catchability coefficients. They can be implemented in columns G to I, rows 8 to 19 on the regulation worksheet. In column G, place a number between 0 and 1 for each of the cohort numbers. This is what is called the gear restriction coefficient and it is named **grrst(i)** in the worksheet. If a value of .7 is introduced, the catchability coefficient will be reduced to 70% of its value. These values are turned on placing the word on in column H. To account for this, the actual equation for the commercial fishing mortality for each cohort includes a "grrst" term.

$$\textbf{F}_\textbf{c}\textbf{(i) = grrst(i)*(qc}_\textbf{i}\textbf{-decay*boats)*boats} \qquad \text{Equation 2'}$$

If the word on is not in column H, grrst equals 1 and there is no effect. However, when the word on is in column H, grrst takes on the value placed in column G and there is a corresponding reduction in commercial fishing mortality.

Commercial mesh restrictions

   Commercial mesh restrictions are introduced by reducing the catchability coefficient by cohort to take into account the number of fish which are able to escape through the net and also the mortality which is imposed on the

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   [4] The programming to accomplish this is relatively simple. The program determines the maximum and minimum of the two regulated seasons and calls the first **maxcolm** and the second **mincolm**. Then the lengths of the three parts of the season will be **mincolm**, **maxcolm-mincolm**, and **NormT-maxcolm**. See columns D and E on the mortality coefficient worksheet. The only other thing left to determine is which of the two sectors will operate during the second part of the season. (Both sectors will operate in the first and none will operate in the last.) This is done defining the fishing mortality to be used as Sector2(i) and then using an if statement to the effect that if $\textbf{T}_\textbf{c}$ = **maxcolm**, let Sector2(i) equal $\textbf{F}_\textbf{c}$, otherwise use $\textbf{F}_\textbf{r}$**.** See column I for cohort 1.

escaped fish. This is introduced in columns J to M, rows 8 to 19 on the Regulation worksheet. Let **mesh(i)** be the percentage of the commercial fishing mortality which remains on the ith cohort after the mesh restriction is introduced. This value is placed in column J. Let **dismort(i)** be the percentage of the fishing mortality which was reduced by the mesh restriction for any cohort which is reintroduced as a result of discard or escape mortality. This value is placed in column M. To allow a particular mesh regulation to affect a certain cohort, place the word on in column L. The equation for commercial fishing mortality becomes:

$$F_c(i) = [qc(i) - decay*Boats]*Boats*grrst(i)*\underline{[mesh(i) + \{1 - mesh(i)\}*dismort(i)]} \qquad (2'')$$

The new term is underlined. If the word on is not in column L for that cohort, mesh(i) will be 1 and the underlined term will be 1. If the word on is in column L for that cohort, the underlined term will reduce $F_c(i)$ by the mesh(i) factor but part of that reduction will be added back in to account for discard mortality.

While this equation for fishing mortality does allow for calculating the change in cohort size over the season, it is necessary to make modifications in the catch equations to capture the difference between catch and landings. To explain this in detail, note that the above fishing mortality equation can be broken into two term:

$$F_c(i) \quad = [qc(i) - decay*Boats]*Boats*grrst(i)*[mesh(i)] +$$
$$[qc(i) - decay*Boats]*Boats*grrst(i)*[\{1 - mesh(i)\}*dismort(i)]$$

The first term calculates landings mortality while the second calculates discard mortality. Define the second term as mesh_discard(i).

$$mesh\_discard(i) = [qc(i) - decay*Boats]*Boats*grrst(i)*[\{1 - mesh(i)\}*dismort(i)]$$

The equation for commercial landings becomes

$$Hc(i) = [F_c(i) - mesh\_discard(i)]/(F_c(i) + F_r(i) + M)*(N_{i,intial} - N_{i,final})$$

The equation for commercial discards is

$$Dc(i) = [mesh\_discard(i)]/(F_c(i) + F_r(i) + M)*(N_{i,intial} - N_{i,final})$$

The simulation model tracks mortality using $F_c(i)$ and it breaks that mortality in to landings and discards using the above equations.

Commercial size limits

A commercial size limit prevents the landing of fish of certain sizes. That is, fish in particular cohorts can not be landed but are returned to the sea. The net effect on commercial fishing mortality depends upon the mortality rate of the fish which are returned. Let **dismortsc(i)** be the percentage of the fish which are returned to the sea which die in cohort i from a commercial size limit on that cohort. In other words, if this value is .8, then 20% of the fish which are released survive. A commercial size limit program can be activated in columns N to P, rows 8 to 19 on the regulation worksheet. Place the value of **dismortsc(i)** in column O and put the word on in the appropriate row for a chosen cohort in column N. To introduce commercial size limits into the calculations, the equations for fishing mortality, commercial landings and commercial discards have to be modified as follows.

$$F_c(i) = [qc(i) - decay*Boats]*Boats*grrst(i)*[mesh(i) + \{1 - mesh(i)\}*dismort(i)]\underline{*dismortsc(i)}$$

$$Hc(i) = [F_c(i) - mesh\_discard(i)]*\underline{csizelim(i)}/(F_c(i) + F_r(i) + M)*(N_{i,intial} - N_{i,final})$$

$$Dc(i) = [mesh\_discard(i)]*\underline{[1 - csizelim(i)]}/(F_c(i) + F_r(i) + M)*(N_{i,intial} - N_{i,final})$$

The new terms are underlined. The commercial fishing mortality is multiplied by **dismortsc(i)** and the landings and the discard equation have a term which includes the parameter **csizelim(i)**. The parameter **csizelim(i)** is an off/on switch for commercial size limits for a particular cohort. It has a value of 1 when there is no commercial size limit and a value of zero when there is a commercial size limit. This parameter is found in Column F, rows 8 to 19 on the Regulation worksheet.

   When the word   on   is not in column N for a particular cohort **dismortsc(i)** takes the value 1 (see column P, rows 8 to 19 on the Regulation worksheet) and **csizelim(i)** also takes the value 1. This means that $F_c(i)$ will not be affected. All fish which are caught remain on board and die. It also means that **Hc(i)** will not be affected, however **Dc(i)** will equal zero. When the word on   is in Column N for a particular cohort, **dismortsc(i)** takes on the value specified in column O, and **csizelim(i)** takes on the value of zero. This means that $F_c(i)$ will be reduced by the amount of fish which survive the discard practice. It also means that all that mortality will be transferred from landings to discards. **Hc(i)** will equal zero, and **Dc(i)** will equal the mortality from fishing taking into account that fish are thrown back and some of them may survive.

Recreational size limits

   Recreational size limits are exactly analogous to commercial size limits both in principle and the way they are handled in the simulation program. They are introduced in Columns Q to S, rows 8 to 19 on the Regulation worksheet. We have **dismortsr(i)** which is the change factor for recreational mortality for a particular cohort due to a size limit and the resultant potential survival discards. We also have **rsizelim(i)** which is the on/off switch for recreational size limits. The user places the value of **dismortsr(i)** in Column R. When the word   on   is not in Column Q, there will be no effect on recreational fishing mortality nor on recreational landings or discards. However, when the word   on   is in column Q, the recreational mortality is reduced, and all mortality is transferred from landings to discards.

Recreational creel limits

   A creel limit constrains the catch per day of recreational fishers. This is a tricky thing to introduce into the model because catch is calculated based on the change in cohort size using instantaneous total mortality and then apportioning that mortality to the two sectors. It is assumed that while creel limits will affect the number of days fished through the WTP equation, it will not affect the actual fishing behavior while they fish other than forcing them to discard any fish once the creel limit is reached. Therefore the change in cohort size and numbers of commercial and recreational catch are calculated in the normal way. Then the difference between total annual recreational catch and the product of the number of recreational participants times the number of days fished times the creel limit is calculated. This is the number of fish which are thrown back. After considering a discard mortality, those that survive are added back into the final cohort size. The details are explained in a step by step process below.

Explanation of creel limit

1. The creel limit is initiated by placing the word   on   in cell A13 on the Regulation worksheet. Anything else or nothing will turn it off. The cell is named   **creelofforon**   .

2. The creel limit number is specified in cell B13. The parameter is named   **creellimit**   .

3. The creel limit for the two recreational groups is found in columns IC and ID on the simulation worksheet. The columns are named   **creel_1**   and **creel_2** respectively. When the creel limit is not on, the cpue is inserted in this column. When the creel limit is on, the minimum of the creel limit and the cpue is entered. This takes into account the case when the stock size is such that the creel limit is non-binding.

4. With the creel limit, it is necessary to distinguish between the amount caught in numbers and the amount landed in numbers. The amount caught for both groups is calculated in the normal way in columns GP and GS respectively. The columns are named   **recnum_grp1**   and **recnum_grp2**, respectively. (Note that the columns

are labeled in plain English to be more descriptive. Naming is a technical EXCEL process which allows for easier programming and interpretation of equations.) The amount landed for each group when the creel limit is on can be calculated as the number of days fished times the number of participants times the creel limit. When the creel limit is off, the number landed is equal to the number caught. These values are in columns GQ and GT, respectively. The columns are named **recnumland_grp1**   and **recnumland_grp2**, respectively.

5. Total recreational catch is found in column GW and is named **recnum_total**. It is the sum of catch from the two groups. Total recreational landings is found in column GX and is named **recnumland_total**. The two will be the same when creel limit is off. The total weight landed is not calculated.

 6. The total number of released fish for each group will be the difference between catch and landings. This is calculated in columns GR and GU respectively. These columns are named **recrelease_grp1** and **recrelease_grp2**, respectively.

7. The recreational discard number will be the number of released fish which suffer mortality. A discard mortality rate by cohort is already specified for the recreational size limit regulation. These numbers are found in column R, Rows 8 though 19 on the regulation worksheet. The average of these rates is calculated in cell R20 and named **avgrecdismort**. The columns which list recreational discards in numbers for each group are HF and HG. The equations which are currently in these columns calculate discard mortality in the standard manner. To consider creel limit discards, a term which multiplies the average discard mortality times the number of fish released by each group has been added. Similarly a term has been added to the columns of weight of discards which multiplies the number of fish which die after release times the average wt of fish. See columns HI and HJ.

8. The number of fish which survive discard with creel limits is calculated in column GV and is named **recnumsurvive**. It is calculated by multiplying the difference between total catch and total landings time (1- average discard mortality). This is the number of fish which do not perish and hence must be added back into the cohorts. That is the number $N_{(final)}(i)$ represents the final number in a cohort after recreational, commercial, and natural mortality. But recreational mortality is based on catch not landings. Therefore it is necessary to add back in the number which survive discard. The number of the surviving fish which belong to each cohort is calculated as follows. The number of the fish from each cohort will be in proportion to the ratio of catchability coefficients for the two groups for any cohort to the sum of the catchability coefficients for both groups over all cohorts. Go to the **data** worksheet and place cell G10 in the upper left hand corner to see the table which includes the recreational catchability coefficients for each group. In cells I28 and J28 the coefficients for each group are summed. The sum of those values is calculated in M28. In column M, the ratio of the sum of the catchability coefficients for the two groups to the number in M28 is calculated. It is named **recharfraci**, for recreational harvest fraction. In order to adjust cohort sizes for the fish which survive discard, the product of **recharfraci*recnumsurvive** is added to $N_{(final)}(i)$ for each of the cohorts. See for example column E.

A Commercial Limited Days at Sea Program
        A commercial limited days at sea program restricts the number of days each boat owner can operate in a season. It is very similar in effect to a commercial season length except that the vessels can choose when they want to operate during the open season. If all vessels choose to use their DAS at the beginning of the season, the effect is identical to a commercial closed season. For purposes here, it will be assumed that the operating vessels choose to spread their DAS over the entire season. For example, assume there are 25 vessels and NormT equal 50. If each boat is given 20 DAS, there will be 20 days*25 boats=500 boat days for the season. If these are spread evenly over the season, there will be 500 boat days/50 days = 10 boats operating on each day during the season. Since boats will vary across time according to entry and exit, the number of boats operating on any day during the season will equal DAS/NormT*Boats. Define DAS/NormT as the DAS coefficient.
        A DAS program can be operationalized by placing the word yes in Cell B8 in the Regulation Worksheet and place the allowed DAS for each boat in Cell B9. With any other word in Cell B8, the DAS program will not be operational. The allowed DAS must be less than NormT or Tc. When yes is placed in Cell B8, the DAS coefficient is calculated in Cell B10. Otherwise the coefficent is equal to 1. Everywhere in the program where harvest, revenues, and costs are calculated, the value for boats is multiplied by the DAS coefficient. This captures the effect of the DAS program on the change in vessel activity as a result of the DAS constraint.

License Limitation

A license limitation program will prevent the fleet from growing beyond the number of licenses issued. A license limitation program can be inserted in the model by placing the word yes in Cell H11 in the Data Worksheet and place the number of licenses issued in Cell H12. When any other word is in Cell H11, the license limitation program will be turned off. If the number of licenses is more than the initial fleet size set in Cell H2, there may be an upper limit on fleet size, depending on how large the fleet will go in no regulations. If the number of licenses is less than the initial fleet, fleet size will immediately fall to the limited number. When the limitation program is in effect, entry to the fleet is stopped at the set amount regardless of profits. One of the weaknesses of license limitation program is the tendency of vessel owners to enlarge the capacity of their vessels when the stock size improves. This phenomenon is not captured in the model. Do not run a licence limitation program simultaneously with an ITQ program.

Commercial TAC

With a TAC the commercial fishery must be shut down when total commercial landings in weight is equal to the TAC. That is, if the TAC is binding, the fishery can not be allowed to operate for NormT days. A TAC program is turned on by placing the word yes in G3 on the Regulation worksheet. Set the desired TAC in cell H3. A set of macros have been programmed to calculate the season length that will be necessary to harvest the TAC. During the operation of the macro, vessel entry and exit will occur according to the profits that result from allowing the boats to operate the calculated number of days.

In some cases, the TAC will not be binding, and it is necessary to take special precautions in using the macro. This can be explained in a step by step manner as follows.

1. Set all of the variables to those that are desired for the status quo to be compared with the TAC. Make sure the ITQ and the fishing mortality control regulation are turned off by placing anything other than the word yes in cells G4 and G5. Push the F9 key to run the run the program with the existing parameters.

2 On the Regulation Worksheet, put yes in Cell G3 and the TAC level in Cell H3.

3. Go to the simulation worksheet and place Cell GM14 in the upper lefthand corner. You should see three purple columns. The third column (column GO) is the one used in the macro to determine the season length that is necessary to have catch equal the TAC. Make sure the value of NormT is placed in all cells in that column. The first column (column GM) shows the annual actual catch in weight for the status quo situation given that the season length equals NormT. The second column (column GN) shows the difference between actual catch and the TAC. If the number is negative it means that given the number of boats and the other parameters, the TAC will be non-binding for that year. That is, it will take a season length longer than NormT to obtain the TAC.

4. As, mentioned, the macro uses the Goal Seek tool to find the season length that will obtain the TAC. If the TAC is non-binding the macro will go into a never-ending cycle because season length can never be longer than NormT. If none of the numbers in Column GN are negative, the TAC is always binding. With the cursor on the simulation page, push the Tools button and select macros. Run the macro entitled TAC. Warning: depending on the speed of the computer, the macro can take as long as 20 minutes to run. If the number in Cell GN15 is negative, run the macro entitled TAC2ndyear. This will leave season length in the first year when the TAC is non-binding equal to NormT, but will calculate the necessary season lengths in the other years. There are also macros entitled TAC3rdyear and TAC4thyear to run if the TAC is non-binding in the first two and the first three years respectively. The program is not set up to handle cases where the TAC is not binding for more than three years, although the solution can be found by adapting the macros or by repetitively using the goal seek tool to find the season length in column GO is such that the value in Column GN is zero.

Care should be taken before starting the macro. Make sure that no other programs are running and push the save button before starting. If the macro causes a never ending loop, the best thing to do is to push the restart button on the computer. After the computer restarts go back in and open the saved file and start again.

Because the macro has to run in order to determine the effects of the TAC program, it is important to realize that just because the word yes is in Cell G3 on the Regulation worksheet, it does not mean that the output of the model will show the effects of the program.

By making some small changes in the program it is also possible to check the effects of a variable TAC program. This will involve a rather tedious process of repetitively using the Goal Seek tool in each year to insure that the desired TAC for that year is achieved.

Individual transferable quotas ("perfect")

With a TAC, the desired catch is obtained by shortening the season taking into account the number of boats. With an ITQ program, the number of full time boats necessary to harvest the TAC, during the normal season length, would tend to fall to the minimum possible, although there would be an adjustment period. To get an idea of where an ITQ program would tend to go, a macro was designed to find the minimum number of boats necessary to harvest the TAC each period. Full time operation is defined as operating Tc days. To run the ITQ program, place yes in Cell G4 on the Regulation worksheet. Make sure that anything but yes is placed in cells G3 and G5 on that page. The operational TAC is set in cell H3. This macro can be initiated by pushing ctrl and lower case I simultaneously. There is no concern for a non-binding situation, as long as the licence limitation option is turned off and the TAC is less than the bioeconomic equilibrium harvest level (see the discussion on model calibration), and so the one macro can cover all situations. The macro can only be initiated when the simulation worksheet is the operative worksheet and it also takes about twenty minutes to run. Again, just because the work yes in Cell G4, the results of the model will not show the effects of an ITQ program unless the macro has been run.

Commercial annual fishing mortality controls

This regulation will find the number of days that the commercial fleet can operate such that commercial annual fishing mortality, defined as the ratio of total commercial catch in weight, (including discards) to the total weight of the standing stock, is equal a predetermined rate. This regulation program is initiated by placing the word yes in Cell G5 on the regulation worksheet and then placing the desired annual commercial mortality rate in Cell H5.

As a frame of reference for setting the desired commercial mortality rate, A time plot of total and commercial fishing mortality rate is exhibited at Cell G1 on the Analysis Worksheet. (A description of how to set up the Analysis Worksheet is provided below.) Make sure the status quo and regulation variables are the same before using the graph. The thin red line plots the commercial fishing mortality rate while the thick red line shows the total mortality rate. The difference is the recreational fishing mortality rate. Use of this regulation will prevent commercial fishing mortality from going above a specified level. Therefore it is necessary to set the restricted commercial fishing mortality rate such that it constrains the system. That is it must be less than the maximum rate achieved. Here again, it is possible that the limit commercial fishing mortality rate may be non-binding in some cases. The procedure for analyzing a limit commercial fishing mortality rate is analogous to analyzing a TAC program.

1. Set all of the variables to those that are desired for the status quo to be compared with the limit commercial fishing mortality rate. . Make sure the ITQ and the TAC regulations are turned off by placing anything other than the word yes in cells G3 and G4 on the Regulation Worksheet.. Push the F9 key to run the run the program with the existing parameters.

2 On the Regulation Worksheet, put yes in Cell G5 and the limit commercial mortality rate in Cell H5

3. Go to the simulation worksheet and make sure that the value for NormT is placed in all cells in Column GO. The macro for this regulation uses the same column as does the TAC regulation. Then place Cell HJ14 in the upper left hand corner. Column HJ shows the annual actual annual commercial fishing mortality rate multiplied by 100 for the status quo situation given that the season length equals NormT. (It is necessary to multiply it by 100 to get the Goal

Seek tool to work. Column HK shows the difference between actual mortality rate and the limit mortality rate, again multiplied by 100. If the number is negative it means that given the number of boats and the other parameters, the limit mortality rate will be non-binding for that year. That is, it will take a season length longer than NormT to obtain the limit mortality rate.

4. As before, the macro uses the Goal Seek tool to find the season length that will obtain the desired mortality rate.. If the limit mortality rate is non-binding the macro will go into a never-ending cycle because season length can never be longer than NormT. If none of the numbers in Column HK are negative, the limit mortality rate is always binding. With the cursor on the simulation page, push the Tools button and select macros. Run the macro entitled mortality. If the number in Cell HK15 is negative, run the macro entitled mortality2ndyear. This will leave season length in the first year when the limit mortality rate is non-binding equal to NormT, but will calculate the necessary season lengths in the other years. There are also macros entitled mortality3rdyear and mortalty4thyear to run if the limit mortality rate is non-binding in the first two and the first three years respectively. The program is not set up to handle cases where the limit mortality rate is not binding for more than three years, although the solution can be found by adapting the macros or by repetitively using the goal seek tool to find the season length in column GO is such that the value in Column HK is zero.

Care should be taken before starting the macro. Make sure that no other programs are running and push the save button before starting. If the macro causes a never ending loop, the best thing to do is to push the restart button on the computer. After the computer restarts go back in and open the saved file and start again.

Model Calibration

The parameters of the model can be calibrated using the file entitled LEMSR. However, due to the complexity of the calculations involved, it is only possible to calibrate a commercial only fishery or a commercial/recreational fishery where there is only one type of recreational participant.

On the worksheet entitled data, enter the same parameters as are found in the LEM41 model, noting that it is only possible to have one type of recreational participant. Then go to sheet 2 and run the macro entitled overall. Through an iterative process this macro determines the equilibrium number of boats that it will take to harvest the surplus that is generated by any given spawning stock taking into account the equilibrium number of recreational fishing days that will be generated at that spawning stock size.

After running the macro, insert the word yes in cell C86 on sheet 2. The run the solver tool as it is set up. Do this by pushing the tools button and selecting solver. When the solver box appears push the solve button. This will solve for the number of boats, the spawning stock size, and the equilibrium number of recreational fishing days per participant, where industry gross profits are equal to zero and the spawning stock size that is generated by the resultant commercial and recreational fishing is equal the initial spawning stock size. This will be the equilibrium where the fleet is just covering variable costs. Type the spawning stock size that shows in cell H91 is cell E86. Then type the word no in Cell C86 and run the solver again. This will calculate the equilibrium where the fleet covers all of its costs. Type the spawning stock size that shows in cell H91 in Cell E84.

Now scroll to the top of the page and observe the graphs which are generated from this results. The first graph shows the sustainable revenue and total cost curve. The bioeconomic equilibrium occurs at the intersection of the two curves. In order for this to be a stable equilibrium, the intersection must occur in the upward sloping portion of the sustainable revenue curve. Even if the equilibrium is technically stable, running the model may not achieve the equilibrium level in the 24 years the LEM41 model runs. The equilibrium fleet size and the commercial and recreational harvest in weight are displayed to the right of the figure. The commercial harvest level is important because any TAC will have to be set lower than this in order to be a long term binding constraint on the fishery.

It is interesting to note that if the decay factor is equal to zero and if the mortality and catchability coefficients are the same for all cohorts, the equilibrium stock size will not change with the number of recreational

participants. Only the equilibrium number of boats will. This is analogous to the Schaefer model where the equilibrium stock size is a constant and equals Cost/price*catchability.

Now scroll down so that you can see the next two figures. The first one shows the equilibrium number of boats for each spawning stock and the second shows the recruitment sustainable spawning stock curve that is displayed in the Popdy worksheet on LEM41. Note that the range of spawning stocks which will support vessels is smaller than the range where the sustainable spawning stock curve is above the 45° line. This is because of the equilibrium recreational harvest that is taken. The two vertical lines show the two equilibrium stock sizes. The blue one shows the equilibrium spawning stock size where all costs are covered. This means that when spawning stock is above that level, the industry will be making profits. The pink line shows the spawning stock size where the fleet will be covering variable costs. At stock sizes between the two the fleet can operate but it will not cover fixed costs. At stock sizes below the pink line, the commercial vessels will not even cover variable costs.

Now scroll down so as to be able to view the next two graphs. The bottom one shows the equilibrium number of fishing days that will be generated given the CPUE and average weights that are generated at different stocks sizes. If the line crosses the horizontal axis, recreational fishing will cease. If the line crosses the axis to the right of the pink or blue line, it means that commercial fishing can cause the stock to fall so low, that recreational fishing will cease. The other curve shows the equilibrium harvest levels that will be generated at different spawning stock sizes. The blue line is commercial catch and the red line is total catch. Below the point where the recreational fishing curve crosses the horizontal axis, all harvest is commercial.

Although the graphs represent equilibrium situations, which may not occur in the running of the model, they can give an indication of what to expect when running the model.

The LEM41 model allows for the opportunity to start the simulations at the bioeconomic equilibrium. As mentioned this can only be done if there is a commercial only fishery, or a commercial/recreational fishery with one type of participant. It will also work if the second type of recreational participant is such that the equilibrium fishing day curve intersects the horizontal axis to the right of the equilibrium spawning stock size. For convenience sake, this is how the model is calibrated for the test runs. On the LEM41 model, go to the data work sheet. Enter the calculated equilibrium stock and fleet size from the LEMSR file into cells C21 and C22 respectively. Then take the initial recreational fishing mortality found in cell A89 on sheet 2 of the LEMSR file and enter it in cell C23 on the date sheet on LEM41. Then if yes is inserted in cell C20, and no is put in cells C15 and C27, the initial stock and the cohort distribution will be the same as at the bioeconomic equilibrium.   If the initial fleet size is set at the equilibrium fleet size, running the model will result in no changes. The equilibrium will be maintained. This may be used as a status quo situation to compare the effects of various regulations.

Note that it is also possible to set any combination of initial cohort sizes. A useful procedure for doing this is as follows. Put yes in C20 and not in C15 and C27, and push F9. This will cause the cohort sizes of the virgin stock and the bioeconomic equilibrium stock to be displayed in columns B and C starting at row 29 on the data worksheet. These can be used as reference points for selecting other initial cohort sizes. Then put no in C15 and C20 and yes in C27, and place the desired initial cohort sizes in column D starting at row 29.

The Analysis Worksheet

The analysis worksheet has been set up to demonstrate the effects of various regulations against any desired status quo situation. It can be used as follows.

1. Set the parameters that are desired for the status quo situation. If the status quo is any of the regulations which require a macro, make sure the appropriate macro has been run. Push the F9 button.

2. Go to the Analysis worksheet and select aaacopy in the name box in the upper left hand corner. This will select the area where all of the desired output parameters are displayed. Push the copy button. Then move the cursor to Cell AA51 on the Analysis worksheet. Push the edit button and select paste special. Select paste values and hit the

ok button. All of the values will be pasted in a range starting at Cell AA51. Scroll up and look at the figures on the worksheet. All of them will have red curves which show how various parameters vary with time with the running of the program.

3. Change any parameter or set up any regulation program and push F9. Observe the graphs on the Analysis sheet. A new blue line will appear which will show the effects of the changes.

Additional meterial for LEM50rs

Methodology for introducing trip limits to LEM model.

Let

T_{max} = Numer of days in the fishing season

d_{adf} = actual time spent fishing on a trip in days

d_d =down time on a trip in days

d_g = time on fishing grounds on a trip in days $\equiv d_{adf} + d_d$

d_t = round trip travel time in days

d_p = time at dock to prepare for trip in days

The number of trips per year, Trip#, can be calculated as follows:

$$\text{Trip\#} = T_{max}/[d_{adf} + d_d + d_t + d_p]$$

The actual number of days fished in a season, D_{season}, which is used to calculate harvest, is

$$D_{season} = \text{Trip\#}\{d_{adf}\}$$

Note that $\partial \text{Trip\#}/\partial d_{adf} < 0$ but $\partial D_{season}/\partial d_{adf} > 0$. This means that a decrease in time spent fishing on a trip, which would occur with a binding trip limit, will increase the number of trips, but decrease the number of actual fishing days per year.

The effects of a trip limit regulation can be introduced into the simulation model as follows. The explanation will be in terms of a one cohort model, but it is straightforward to extend it to a multi-cohort model.

Let

B = number of boats
$N_i(t)$ = initial number of individuals in cohort in year t
$N_f(t)$ = initial number of individuals in cohort in year t
w = weight of individual fish
q = instantaneous catchability coefficient
M = instantaneous natural mortality coefficient
H = harvest in numbers
H_w = harvest in weight
TL = Trip Limit in weight

$$N_f(t) = N_i(t)e^{-[Bq(Dseason/Tmax)+M]Tmax}$$

That is natural mortality will be working for the whole season, but not so for fishing mortality. Given the fleet size and the catchability coefficient, there is the potential for Bq mortality per day. However, if the boats spread their actual fishing days evenly over the season then the fraction, D_{season}/T_{max}, of that killing power will be working on given day during the season.   Total harvest in number and weight are calculated as follows.

$$H(t)= [N_i(t) - N_f(t)][[Bq(D_{season}/T_{max})]/(BqD_{seaspm}/T_{max}+ M)]$$

$$H_w(t) = H(t)*w$$

Harvest per trip per boat can be calculated as

$$Tripcatch =[H_w(t)]/[B*Trip\#]$$

By using goal seek, it is possible to find a d_{adf} such that trip catch is equal to the trip limit. A macro has been set up to do this for both fleets. The problem is that the solution will change with changes in season length and catch in the recreational sector. However, by running the com TAC macro, the rec TAC macro, and the two trip limit macros several times it is possible to find a overall solution to how many days can be fished in both sectors, and how many actual days per trip it will be necessary to fish in both types of commercial boats to take their respective trip limits.

Basics of how two fleets were introduced.

The basic mortality equation is

$$N_{i, final} = N_{i,intial}*e^{-(com\_expi+rec\_expi+m)t}$$

Where com_expi and rec_expi are the commercial and recreational exponent for the ith cohort, respectively. This is the way they are labeled in the worksheet, but in the earlier handbook, I called them F_c and F_r, The general equation for com_expi is

$$com\_expi = qc_{i*}boats$$

where qc_i is the commercial catchability coefficient for the ith cohort, (a constant) and boats is the number of boats, which varies with vessel exit and entry. The catchability coefficient for the single type of boat are set on the data worksheet. Note, that there are a considerable number of mofications to this equations to handle regulations, but they can be ignored for purposes of this discussion. The values for the exponents are calculated on a worksheet entitled catchability coefficients. In order to save all the trouble of writing the program over to have two types of commercial boats, I did the following.

1. Set the value of boats equal to 1 and then protected the cell so that it can not be changed. This is just a lot easier to do that try to go through the model and eliminate the term whereever it shows up.

2. Introduce new parameters for the the size of two fleets, fleet_a and fleet_b. Right now, they are constants because of the nature of the red snapper fishery, but we could make them change with exit and entry.

3. Introduce two set of constant catchability coeffecients for each of the new fleets. These will be called qcai and qcbi for i equal 1 to 12.The other set will be written out as described below.

The notion is to replace the qc_i, the constant in the above equation, with a parameter called qciperiod, which is calculated each period on the new worksheet entitled commercial sector.

$$qciperiod = fleet\_a*qcai*(Dseason\_a/Op\_T\_com)+$$
$$fleet\_b*qcbi*(Dseason\_b/Op\_T\_com)$$

where Op_T_com is the operational commercial season when there is a TAC. This captures the effect of both of the new fleets into one parameter.

4. The parameter qciperiod is substituted for qc_i in the expression for com_expi above, which means that the values on the catchability worksheet take the calculations of qciperiod on commercial sector worksheet into account.

5. The calculations for splitting the season into three parts when the seasons for the two sectors are not the same and for introducing the various types or regulations are the same as with the earlier model.