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Abstract--*This paper presents a model of the dynamic behavior of the yellowtail rockfish of the Pacific Coast of the United States. The purpose of the model is to generate endogenously the historical data for fish population, fishing vessels, regulatory parameters, and fish harvest. The model was subjected to a variety of tests to determine its sensitivity to changes in key parameters and initial values, including extreme conditions. Model results indicate that acceptable biological catch and fleet capacity must be adjusted quickly in response to changing conditions, in order to improve fishery sustainability. Additional analysis reinforces the policy of setting the maximum sustainable yield at 40%.*

Key words: fishery, yellowtail, rockfish, groundfish, sustainability, fleet reduction.

THE PROBLEM

Populations of rockfish and other Pacific Coast groundfish have dropped dramatically in recent decades. Although the direct economic contribution at the state level (California, Oregon, and Washington) is quite small (1%-3%), the fishing industry is still very important to the coastal communities where it continues to be the mainstay of their local economy.

Northwest communities that are very dependent on natural resource-based industry exhibit low economic growth compared with national average rates. For example, the per capita net earnings in Tillamook, OR, Coos Bay, OR, and Gray's Harbor, WA are below state and national levels (The Research Group 1999).

Since 1983, groundfish revenues have fallen by 69% and landings of rockfish (a type of groundfish) have decreased 78%. Catch limits for various species of rockfish have declined 78%-89%, showing the negative trends in general for the fishery industry as a consequence of inadequate management decisions. To prevent economic collapse, the federal and state governments created several regulations implementing the conservation and community viability provisions of the Magnuson-Stevens Fishery Conservation Act (1996) and its amendments.

Despite these efforts, in January 2000 the West Coast groundfish fisheries were declared a federal disaster (Ecoworld 2000). The decline in fish stocks is considered by many to be the consequence of ineffective natural resource management and short-term policies that resulted in a larger fishing fleet than could be supported long term. These polices are not only affecting the ecosystems, but also the fisheries and associated fishing communities. In his report declaring the fisheries a disaster, Secretary of Commerce William Daley called for alternative management policies to be studied in order to find a way to protect and rebuild fish stocks, while minimizing adverse economic and social impacts on the fishing communities.

Overcapitalization is considered to be the primary cause of the decline in fish stocks for the last three decades. The challenge is how to reduce the fleet without painful economic effects. According to the Pacific Fishery Management Council, the specific objective is to reduce the fleet by 50%, mitigating the adverse effects during the transition (PFMC 2000).

Currently, a number of programs and organizations are working together to formulate the best solution for addressing fleet overcapitalization (Young 2001; PMCC and Ecotrust 2002). In a study of the overcapitalization of the Norwegian fishery (Moxnes 1998) the capacity of the fishery was estimated to be about twice the optimal size for the past fifteen years, and sustainability was threatened because participants consistently overbuilt the fishing fleet. This is an example of "misperception of feedback" (Sterman 1989), and is indicative of the poor performance by participants in managing complex systems in general.

We present a model that demonstrates how system dynamics (SD) could be used to help evaluate policy options for improving the sustainability of the Pacific Coast groundfish fishery and ecosystem. SD is well suited for studying this type of problem because of its ability to characterize dynamic interrelationships between system components and to show how these interrelationships lead to the aggregate behavior of the system as a whole.

BACKGROUND

Mathematics, statistics, computer simulation, and SD have all been used to model fishery management systems. Schaefer (1954) provided the classic dynamic (differential equation) model for fish biomass as a function of pristine (unfished) biomass, intrinsic rate of increase, fishing effectiveness, and fishing effort. The formula was advantageous to the fishery because it required less statistical data; however, the formula did not address the inverse effect of fish abundance on the fishing effort that caused the maximum sustainable yield (MSY) calculations to be biased.

Another classic work is Fish Banks, Ltd. (Meadows et al 1986), an SD-based microworld in which participants attempt to manage a fishery. In the Fish Banks, Ltd. game, teams of players manage their own fishing companies. At the beginning of the game, each fishing company has equal amounts of money and fishing vessels. Each company has the same operating costs and technology. At the beginning of every simulated year, the teams make decisions about buying or selling vessels, whether to fish or not, and where to fish. The object of the game for each company is to maximize profits.

More recent applications of SD to fisheries management include Ruth and Lindholm (1996) who applied SD to multispecies fishery management; Holland and Brazee (1996) and Dudley and Soderquist (1999) who presented an SD-based general fishery model as a tool for studying fishery management policy; Ford (1999) who offered the "Tucannon harvesting model" as an illustration of the application of SD to fisheries; and Sampson (2001) who provided a detailed cohort-based SD simulator for exploring fish harvesting policies.

Two very interesting simulators that take into account the interplay between ecosystems and economic systems are the Patagonia Coastal Zone Management Model (van den Belt 1999) and

Otter Trawler (Gates 2000). The former is an elaborate SD-based simulator, whereas the latter is not SD based.

Figure 1 shows a high-level description of the interplay between the ecosystem, fishery, and fishing community that guided our study of groundfish sustainability.

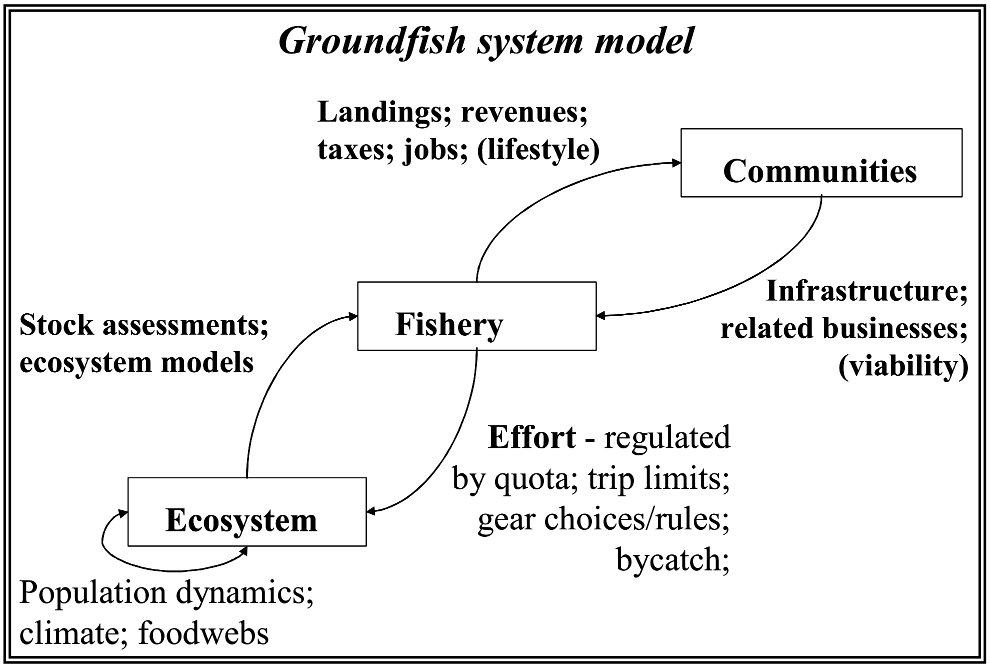


Figure 1 - Groundfish Subsystems

Selected Definitions

- *Acceptable Biological Catch (ABC)*: An estimate of the amount of fish in tons that could be taken from a stock at its current abundance without jeopardizing it. ABC is calculated by multiplying current biomass by the harvest fraction that would produce the MSY.

- *Annual Recruitment*: The number of fish that mature and become vulnerable to fishing in a given year.

- *Maximum Sustainable Yield (MSY)*: The largest average catch or yield that can continuously be taken from a stock under existing environmental conditions. For species with fluctuating recruitment, the maximum might be obtained by taking fewer fish in some years than in others.

- B_{MSY}: The biomass value that corresponds to MSY.

- *Stock Assessment and Fishery Evaluation (SAFE) Reports*: Reports that provide historical data on catch and biomass for various species of fish.

- *Trawl vessels*: Vessels that primarily use trawl gear and account for the majority of groundfish landings (approximately 90%).

Reference Behavior Pattern

The species chosen for this model is the Pacific yellowtail *(sebastes flavidus)*, a type of rockfish. Historical data from various sources (PFMC 1981-2003; Taggart 2000; NOAA 1996; NMFS 1998) were used to determine the reference behavior for yellowtail harvest and ABC (see Figure 2).

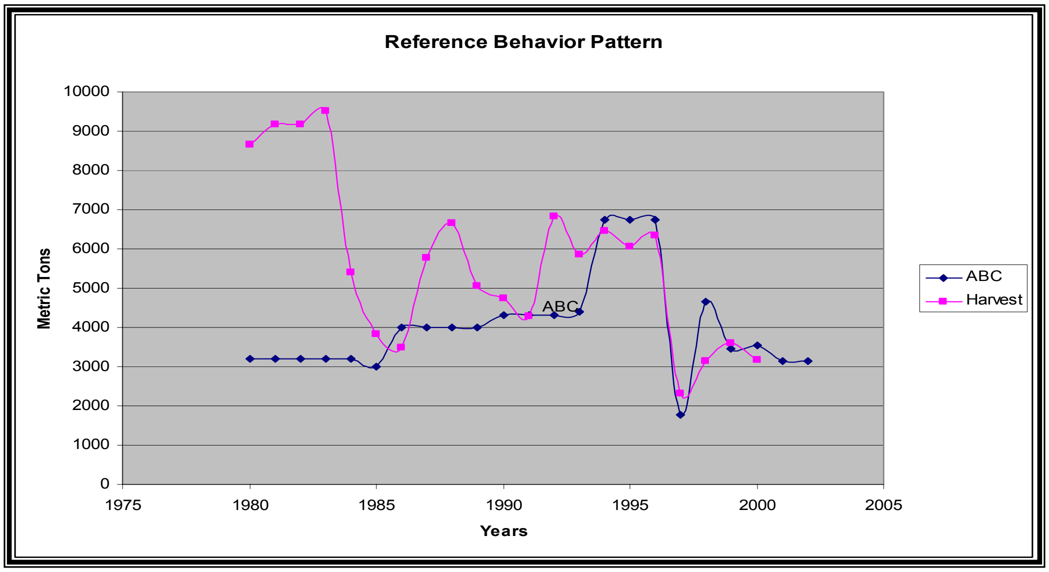


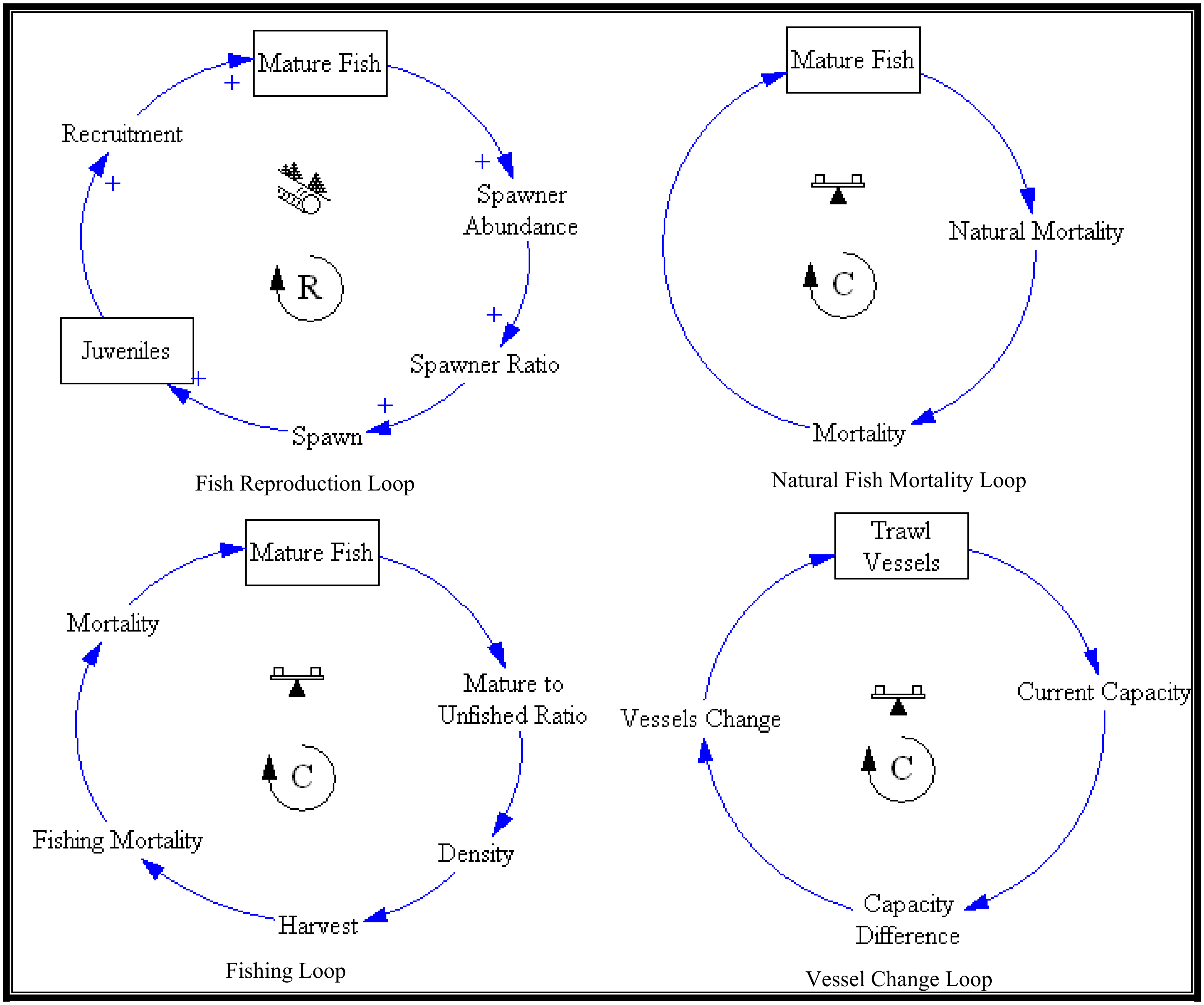
Figure 2– Reference behavior for yellowtail ABC and Harvest

The reference data for the number of trawl vessels fishing for yellowtail is estimated from various sources (NOAA 1996; Young 2001; PMCC 2002), and shows a 72% decline. Other sources (Hanna 2000; Tagart 2000; PSMFC 2000) confirm this decline, indicating that rockfish landing vessels, in general, have declined 78% and that there has been a 69% decrease in gross revenues.

THE MODEL

A system dynamics model is a set of relationships between key variables that are expressed in terms of differential and algebraic equations that are solved numerically to simulate behavior over time. Our model consists of six sectors: the fish population sector, the trawl vessels sector, the ABC sector, the harvest sector, the economic sector, and the ocean health sector. Each sector will be described in the pages that following, but first the primary feedback loops in the model are discussed (see Figure 3).

The reproduction loop is a reinforcing cycle in which mature fish impact the spawning process, which in turn impacts juveniles and therefore mature fish via the recruitment process. The natural mortality loop is a balancing cycle impacting the mature fish. The fishing loop is a balancing loop wherein fishing is reduced when fish population is low, and vice versa. The trawl vessel loop is also a balancing cycle and reflects the number of vessels being reduced when total capacity is more than the ABC, and vice versa. Figure 4 summarizes the overall causal structure of the model.



Fish Reproduction Loop

Natural Fish Mortality Loop

Fishing Loop

Vessel Change Loop

Figure 3- Primary feedback loops

Key Assumptions

The following key assumptions were made:

- *Random variations:* The model uses average values from historical information for recruitment rate, spawning, and mortality fish, and ignores random variations.

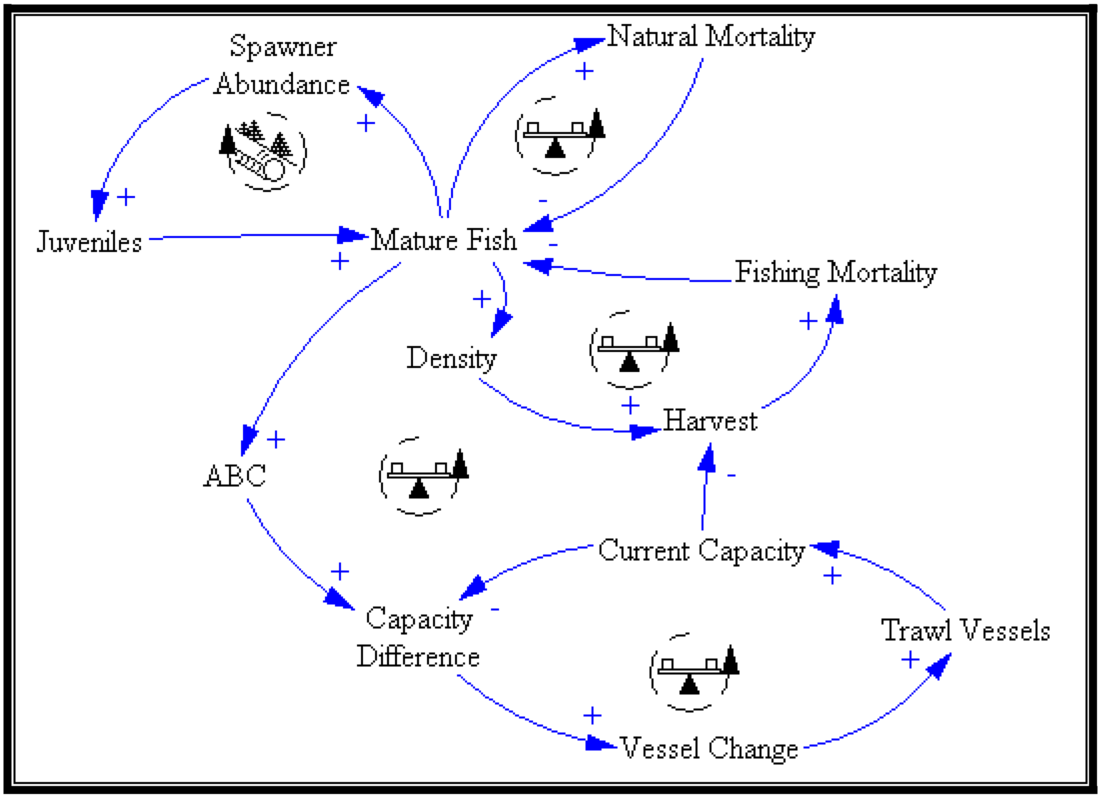


Figure 4 – Overall causal loop structure

- *Ecosystem impact*: The model assumes that fluctuations in ecological variables impact natural mortality rates by a maximum of 20%.

- *Vessels*: The number of trawl vessels in the model is assumed to be a fraction of the total number of trawl vessels in use. This fraction is computed to represent the equivalent number of trawl vessels that would be present if the vessels were fishing only for yellowtail.

- *ABC*: Acceptable biological catch is calculated yearly in the model, based on triennial biomass surveys. This is the established scientific protocol for stocks assessments, although it is not always reflected in actual policy.

Trawl Vessel Dynamics

Trawl vessels are modeled as a stock that could increase or decrease over time. In reality, new trawl vessels do not enter the fleet. Instead, vessels modify their participation season by season. The change in trawl vessels is modeled as a function of supply and demand--vessels increase when additional capacity can be supported and vice versa. In other words, new vessels are added to the fleet when fish are plentiful and removed from the fleet when fish stocks are down.

Current Capacity is the sum of vessel capacity for each of the trawl vessels in the yellowtail fishery. This number is calculated assuming that the total number of trawl vessels working in the yellowtail fishery is a percentage of the total number of groundfish vessels. *Capacity Difference* is the value of the difference between the ABC and the *Current Capacity*.

Management Response Time (MRT) determines how quickly the *Capacity Difference* is reduced to zero. The number of trawl vessels is not changed instantly, rather, a time constant (MRT) is specified to indicate the average time that it takes vessels to enter into and exit from the fleet.

Formulas 1 through 3 summarize the logic, and Figure 5 shows the flow diagram for the trawl vessel dynamics.

$$Capacity\_Difference = CurrentCapacity - ABC \tag{1}$$

$$CurrentCapacity = AvVesselCap * TrawlVessels \tag{2}$$

$$Vessel\ Change = INTEGER(PULSE((CapacityDiff/AvVesselCap)/(MangmtRespTime), 1983, 3)) \tag{3}$$

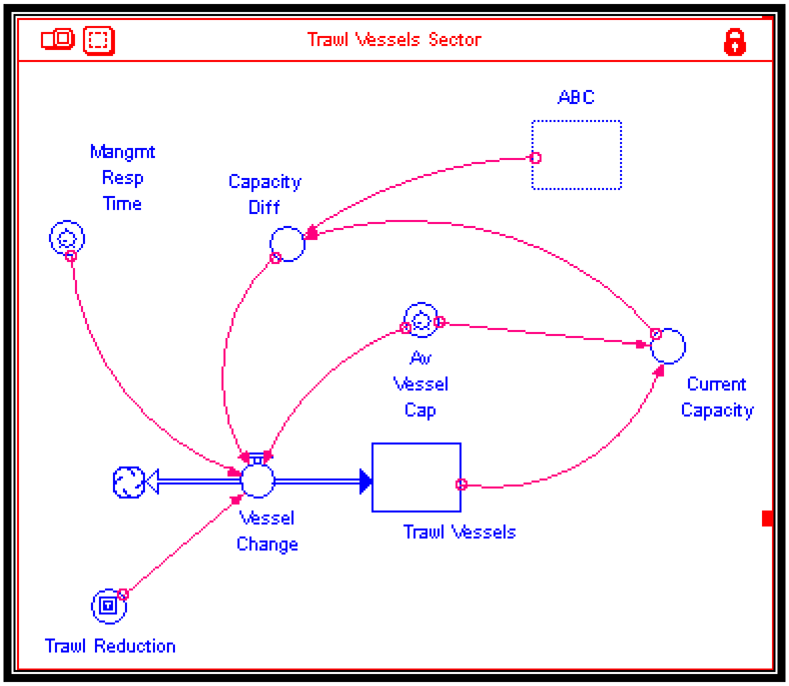


Figure 5 – Trawl Vessel Sector

Fish Population Dynamics (Biomass)

Fish population, often described as biomass, is modeled as two separate stocks, *Juveniles* and *Mature Fish*. The inflow to *Juveniles* depends on a spawning process that considers *Spawner Abundance*, *Pristine Spawner Abundance*, *Maximum Spawn Rate*, and *Spawning Variability*. *Pristine Spawner Abundance* is an indication of carrying capacity (Ford 1999). *Spawns* flow into the *Juveniles* stock, and *Juveniles* flow into the *Mature Fish* stock. The *Juveniles* stock also has a mortality outflow determined by the *Juvenile Mortality Rate,* which is determined by the *Ocean Health Measure*. Mature fish *Mortality* includes *Fishing Mortality* and *Natural Mortality*. *Natural Mortality* depends on *Mature Fish* and the *Natural Mortality Rate,* while

Fishing Mortality depends on *Harvest* and *Bycatch Rate*. Figure 6 displays the flow diagram of the fish population sector.

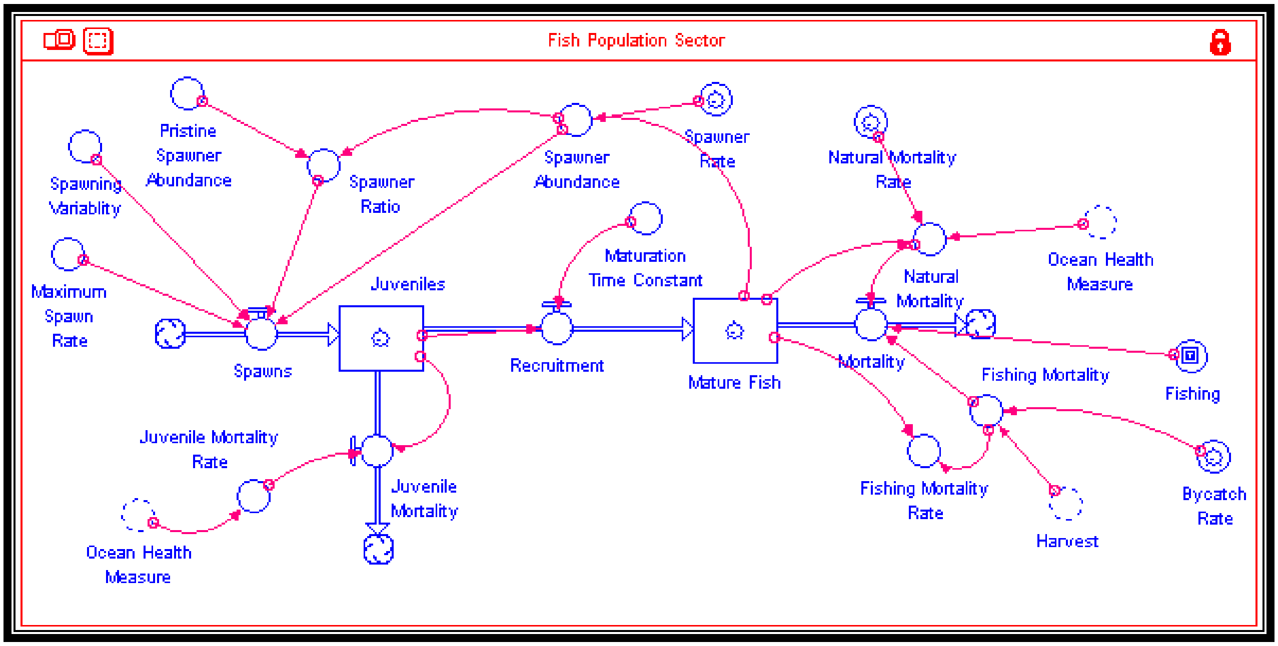


Figure 6 – Fish Population Sector

When there is no fishing, biomass increase to an upper limit where *Natural Mortality* equals *Recruitment,* and *Recruitment* plus *Juvenile Mortality* equals *Spawns*. This equilibrium point is called the unfished (pristine) biomass of the specific fish species. In our case, Yellowtail Rockfish has an unfished biomass of 114,700 Metric Tons (Taggart 2000).

Formulas 4 through 9 pertain to the Fish Population Sector (Figure 6).

$$NaturalMortality = (NaturalMortalityRate*MatureFish)/OceanHealthMeasure \tag{4}$$

$$SpawnerAbundance = MatureFish*SpawnerRate \tag{5}$$

$$SpawnerRatio = SpawnerAbundance/PristineSpawnerAbundance \tag{6}$$

$$Recruitment = Juveniles/MaturationTimeConstant \tag{7}$$

$$Spawns=EXP(-1.73*SpawnerRatio)*MaximumSpawnRate*SpawnerAbundance*SpawningVar \tag{8}$$

ABC and Harvest Logic

The Pacific Fishery Management Council (PFMC) sets ABC based on prescribed rules, the triennial SAFE surveys, and other pertinent information. The model attempts to replicate this process, as indicated in Equation 9. Figure 7 shows the flow diagram for this part of the model.

$$\begin{aligned} ABC = {} & \text{IF } SpawnerPercentage > MSY \text{ THEN } 0.21 * MatureFish \text{ ELSE} \\ & \text{IF } SpawnerPercentage > 0.25 \text{ THEN } 0.12 * MatureFish \text{ ELSE} \\ & \text{IF } SpawnerPercentage > 0.1 \text{ THEN } 0.06 * MatureFish \text{ ELSE } 0 \end{aligned} \tag{9}$$

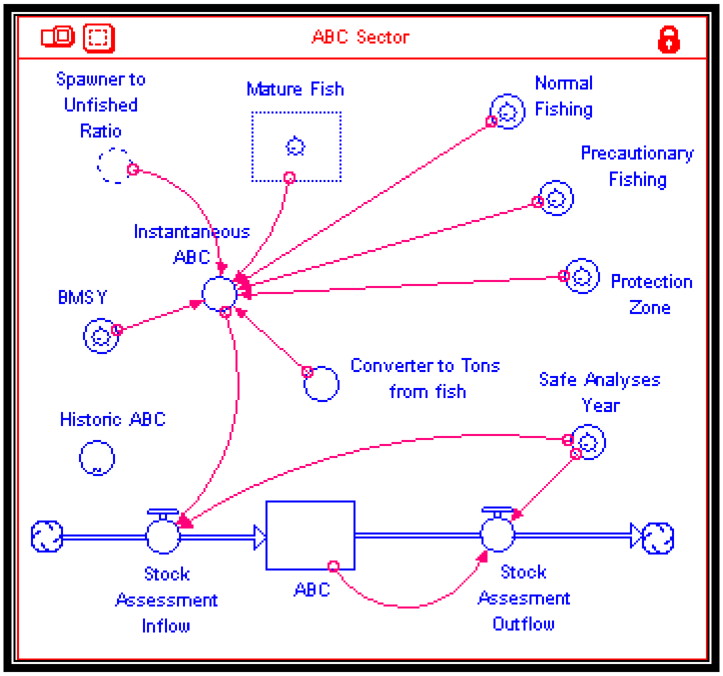


Figure 7 – Flow diagram for ABC Sector

Harvest is determined using *Current Capacity, Restrictions,* and *Density*. This approach is different than what is often reported in the literature, where fishing mortality is modeled as a constant fraction of current biomass. Equation 10 provides the formula for *Harvest* in our model.

$$Harvest = (CurrentCapacity-(Restrictions/Density)) \tag{10}$$

Density is the *Mature to Exploitable Ratio* divided by the *Fish Density Coefficient*. *Mature to Exploitable Ratio* is the current exploitable biomass (*Mature Fish*) divided by *Unfished Exploitable Abundance*. *Density* is treated as zero when there are no *Mature Fish*. Formulas 11 and 12 summarize these relationships.

$$Restrictions = CapacityDifference*TripLimitsEfficiency \tag{11}$$

$$Density = MaturetoUnfishedRatio/FishDensityCoefficent \tag{12}$$

Figure 8 provides the flow diagram for the Harvest Sector.

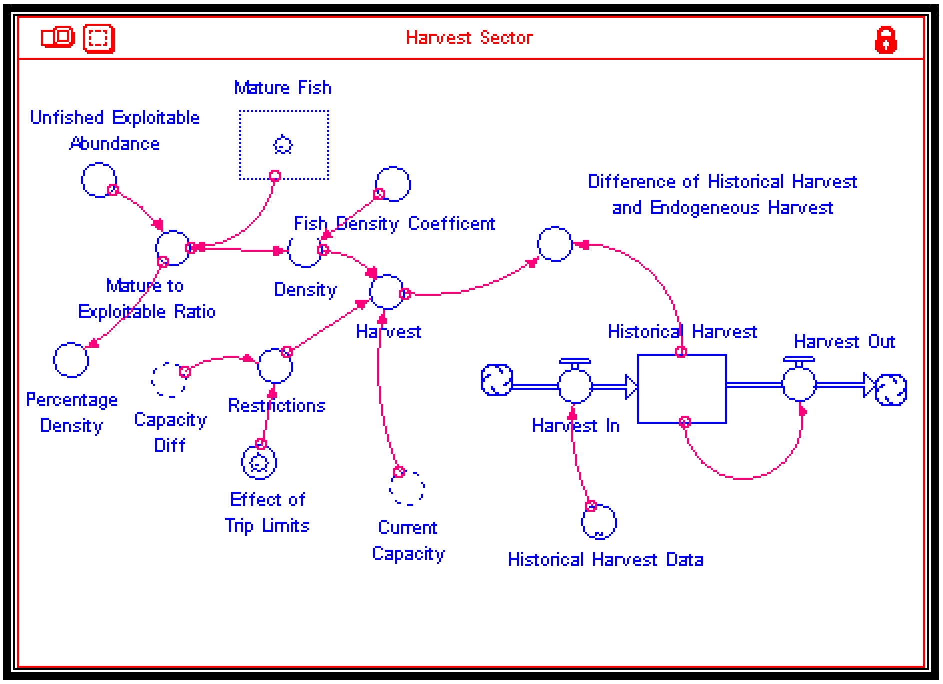


Figure 8 – Flow diagram for Harvest Sector

The Economic Sector

This sector does not participate in the loop structure and simply translates harvest into revenues and profits.

Harvest determines *Fleet Gross Revenues* based on a conversion factor and the *ExVessel Price* for fish. Revenues are accumulated to facilitate the comparison of different scenarios with respect to *Total Gross Revenue*.

Formulas 13 through 15 summarize the Economic Sector (Figure 9).

$$FleetGrossRevenue = Harvest * TonsToPounds * ExVesselPrice \quad (13)$$

$$NetPerVessel = (1\text{-}OperationalCostPercentage) * RevenuePerVessel \quad (14)$$

$$RevenuePerVessel = FleetGrossRevenue / TrawlVessels \quad (15)$$

Ocean Health Sector

According to the literature, many factors including temperature, industrial disposal, El Nino, and ocean nutrient level impact spawning and mortality rates for both juvenile and mature fish (COE 2002; NODC 2002; Ruth et al 2001). The model uses a composite *Ocean Health Measure* to represent these combined effects. *Disposal Effect* and *El Nino Anomalies* are purely exogenous, whereas *Habitat Health* is endogenously calculated, and depends on the ratio of the current value of *Trawl Vessels* to the initial value of *Trawl Vessels.*

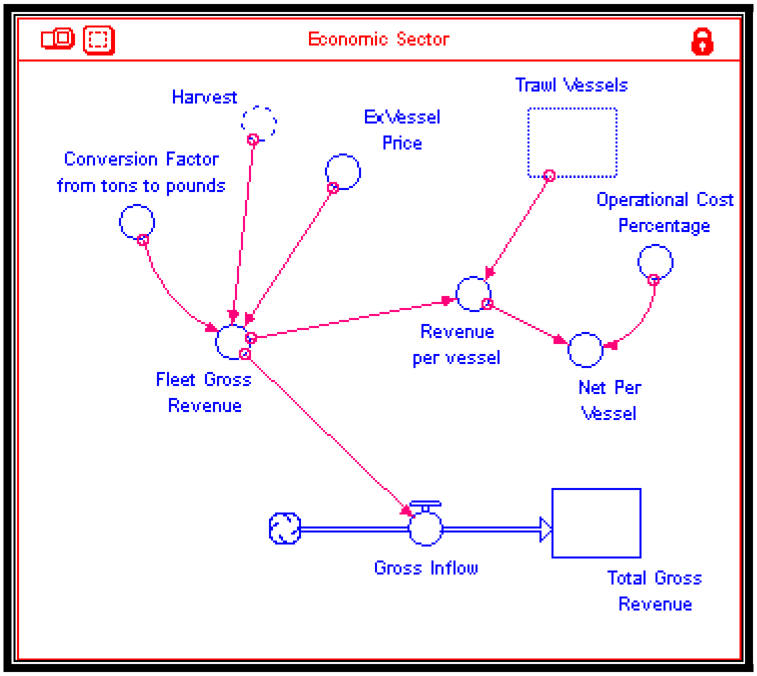


Figure 9 – Economic Sector

One anomaly, El Nino, is generally regarded to have drastically impacted the environment. It changed biomasses, habitats, temperature, and much more. The effects were often to decrease the harvest as well as fish biomass. Data regarding the El Nino effect shows the peak impact to have occurred during 1983 and 1994. This data was normalized and entered in the model as the graphical function *El Nino Anomalies*.

Industrial Disposal rates (COE 2002) are believed to influence fish mortality and spawning. These relationships have not been thoroughly researched. We chose to represent the relationship qualitatively, with a *Disposal Effect* variable that impacts *Ocean Health Measure*.

Our research indicated that disturbing fish habitat reduces spawning and increases natural mortality, since the fish are less able to protect themselves under rocks and other features of the pristine ocean bottom. In particular, trawling the bottom of the ocean tends to destroy the protective layer of the ocean bottom, thereby reducing the health of the fish habitat. This increases the natural mortality rates for groundfish, especially rockfish.

Equations 16 through 20 and Figure 10 represent the Ocean Health Sector.

$$OceanHealthMeasure = HabitatHealth + DisposaEffect + ElNinoEffect \tag{16}$$

$$DisposalEffect = DisposalScalingParameter * DisposalCondition + 0.2777 \tag{17}$$

$$ElNinoEffect = ElNinoScalingParameter * ElNinoAnomalies + 0.2777 \tag{18}$$

$$HabitatHealth = HabitatConditionParameter * HabitatCondition + 0.277 \tag{19}$$

$$\mathit{HabitatCondition} = \mathit{TrawlVessels}/\mathit{InitialVesselAmount} \tag{20}$$

The formulas above assume that each component of the *Ocean Health Measure* (OHM) contributes equally to the measure. Scaling parameters and constants are used to assure that OHM remains within 20% of 1.0.

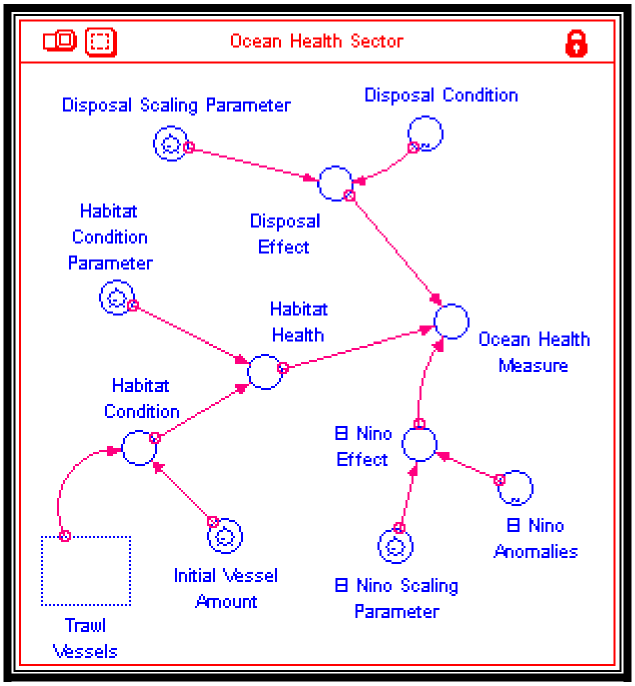


Figure 10 – Ocean Health Sector

Base Model Behavior

Figure 11 compares *Harvest* calculated in the model with the *Historical Harvest Data*. The overall trend is downward in both cases, but there are appreciable differences.

Figure 12 compares *ABC* calculated in the model with the *Historical ABC* from SAFE.

It may be misleading to compare the two traces in Figure 12 because in the model, *ABC* was calculated to maintain fish stocks without regard to economic impact, whereas the *Historical ABC* reflects the complex reality of fishery policy.

Finally, the model indicated a decline in *Trawl Vessels* from 300 to 91 between 1980 and 2002, a 70% reduction (see Figure 13). This result is consistent with the reference behavior discussed earlier.

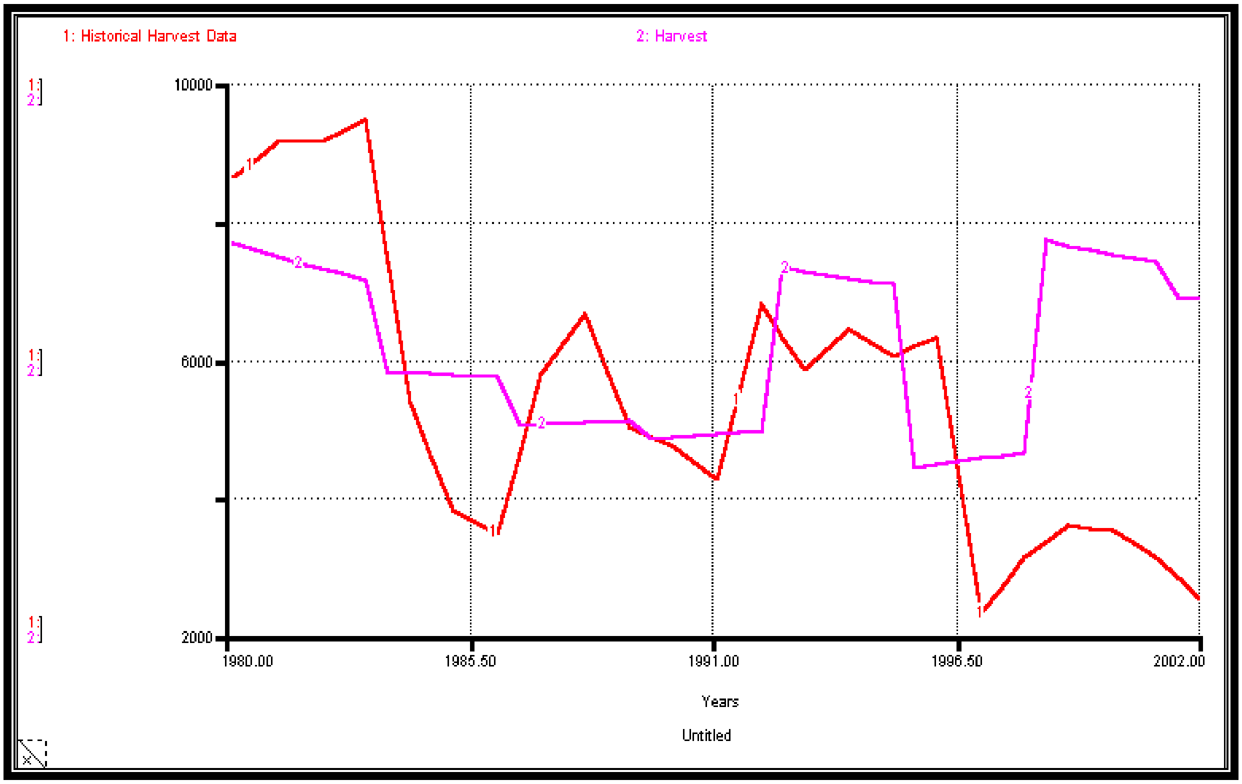


Figure 11 – Harvest, model vs. historical data

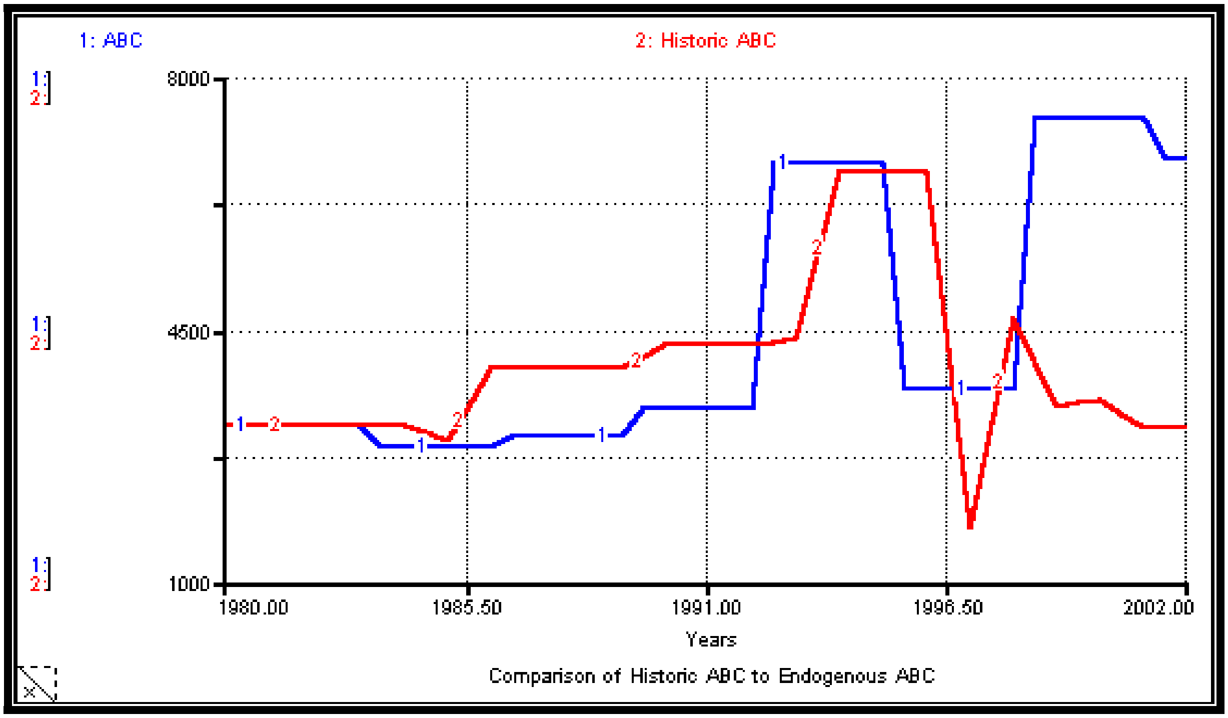


Figure 12– ABC, model vs. historical data

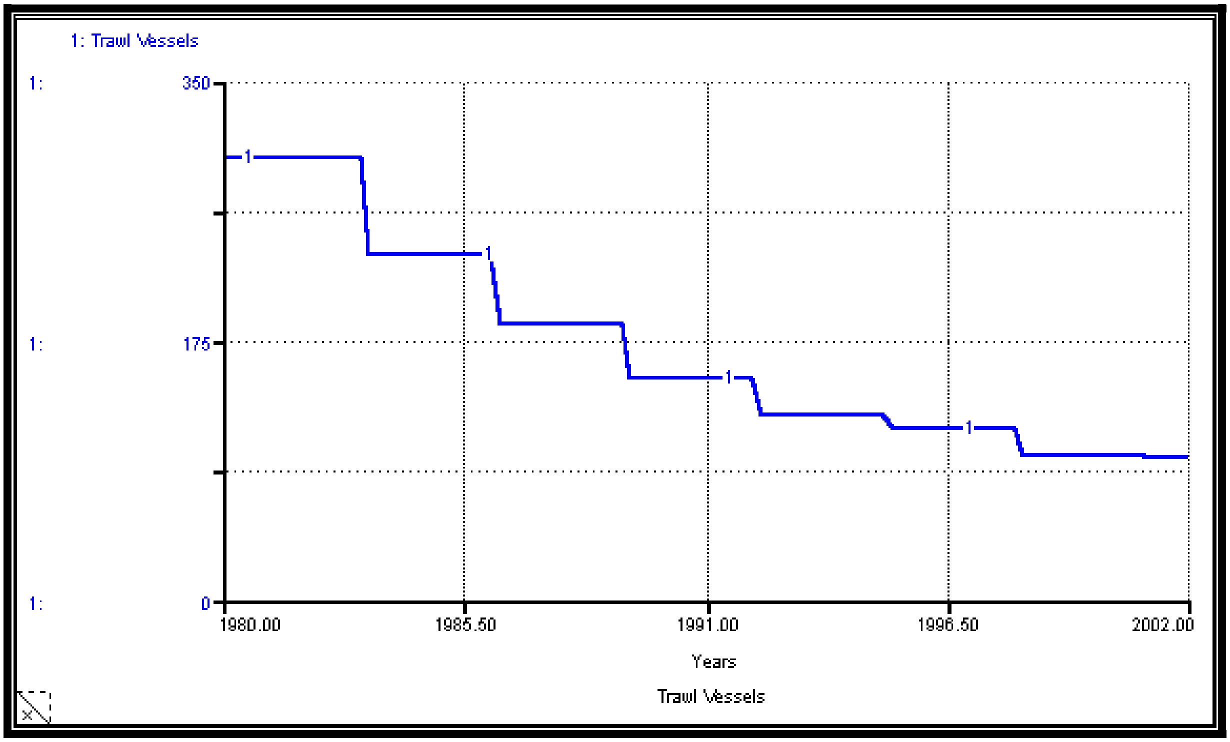


Figure 13– Trawl Vessels over time calculated by the model

MODEL TESTING

The primary focus of our model testing to date has been to thoroughly test the sensitivity of the model to changes in key parameters. The values of each parameter selected were varied over a range 50% below to 50% above the base value. For each value of the selected parameter, we plotted the biomass over time, and show, in the table below the plot, the cumulative *Total Gross Revenue* (*TGR*) in millions of dollars.

Sensitivity Analyses

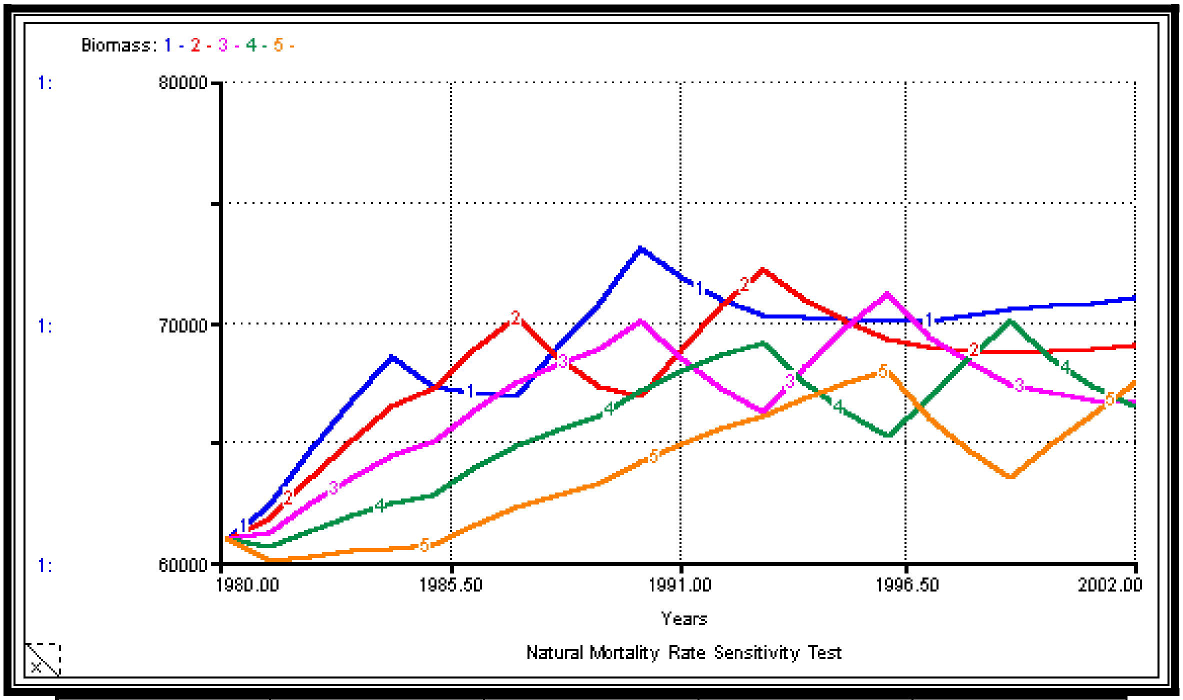
Sensitivity Analysis of *Natural Mortality Rate (NMR)*

The sensitivity of the model to *NMR* is tested by varying its value from 0.05 to 0.15, in increments of .025. Figure 14 shows how *NMR* affects biomass and *TGR*. Increasing *NMR* reduces the *TGR* and significantly impacts the biomass.

This result is consistent with our expectations because *NMR* is an important variable that determines the equilibrium value for biomass in the model.

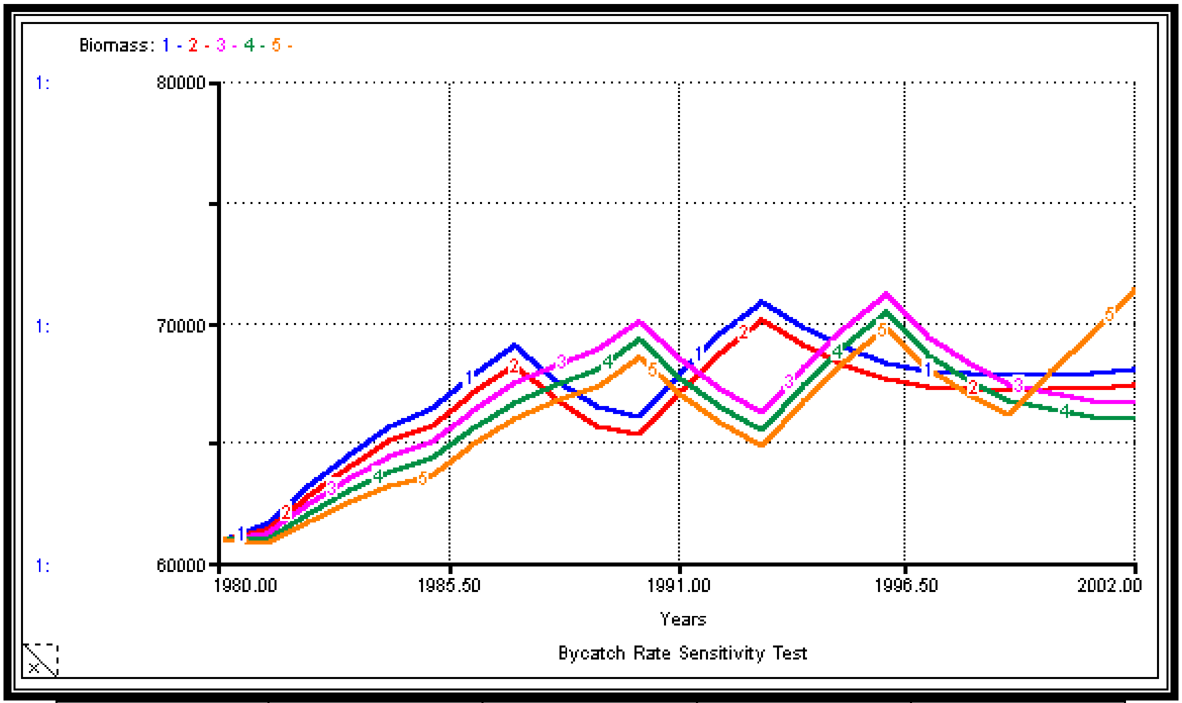
Sensitivity Analysis of *Bycatch Rate*

As shown in Figure 15, the model is less sensitive to *Bycatch Rate,* which was varied from .06 to .18. The fluctuation differences between the runs are the due to delays in the triennial ABC



1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
132,338,296.16	122,078,006.26	112,609,462.49	101,857,893.18	91,188,039.49

Figure 14– Natural Mortality sensitivity test results



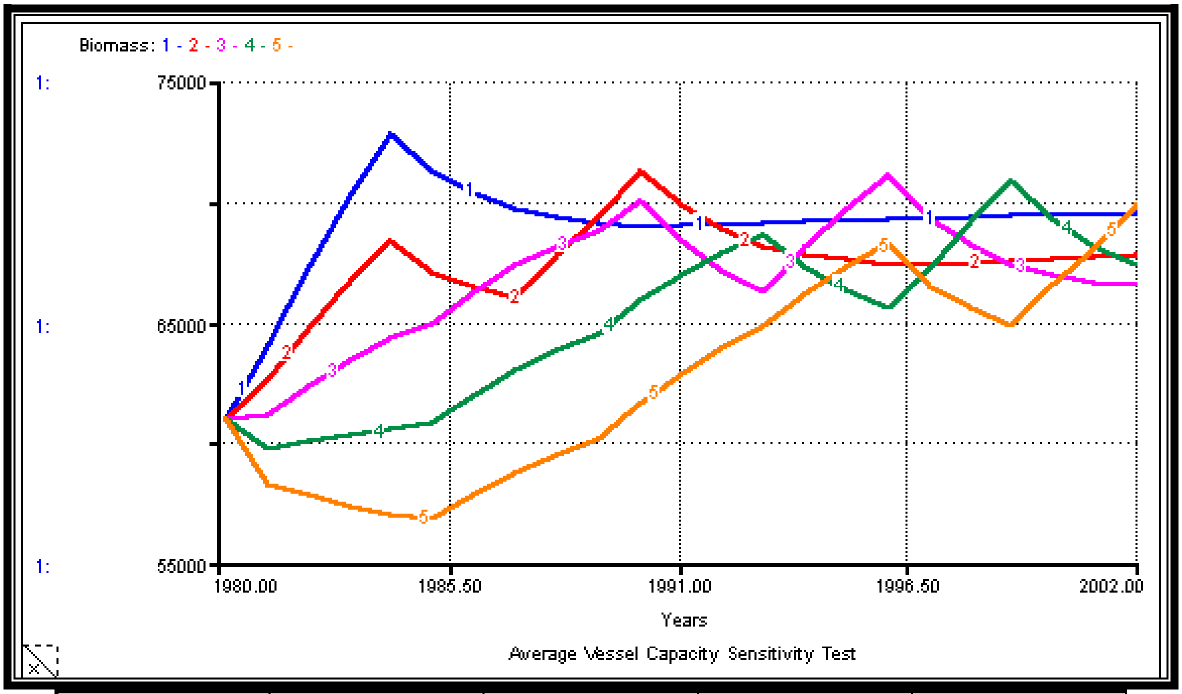
1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
118,193,172.04	115,195,348.35	112,609,462.49	109,943,613.72	103,701,921.13

Figure 15– Bycatch Rate sensitivity test results

determination process. *Bycatch Rate* is an important aspect of fish mortality, and the model should reflect some degree of sensitivity, but, as indicated by the tests, the impact is less than *NMR*.

Sensitivity Analysis of *Average Vessel Capacity (AVC)*

The effect of *AVC* on *Biomass* is displayed in the Figure 16. *AVC* is varied from 40 to 120 tons. The higher the *AVC*, the longer it takes to reach a sustainable equilibrium. However, the *TGR* is not affected significantly by *AVC* changes, due to the balancing loop that reduces the excess capacity (implemented as *Vessel Change* within the model). *Biomass* is more sensitive than *TGR* to changes in *AVC*.

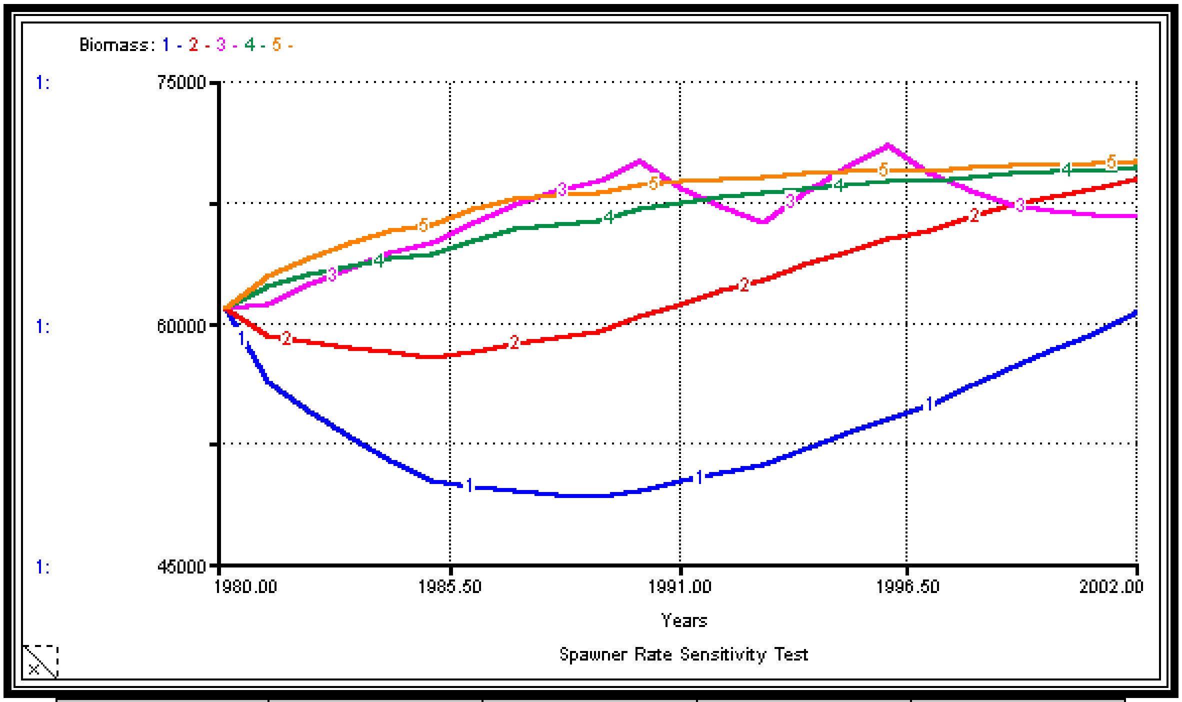


1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
113,585,620.30	112,854,338.86	112,609,462.49	110,901,733.95	107,870,719.24

Figure 16– Average Vessel Capacity sensitivity test results

Sensitivity Analysis of *Spawner Rate (SR)*

The model is very sensitive the parameter *SR* when it is varied from .2 to .6 (see Figure 17). The system reaches equilibrium earlier when the *SR* is higher. *SR* strengthens the only reinforcing loop in the model--a loop that the entire fishery depends upon. The *TGR* values show high sensitivity to changes in *SR*. This effect is not symmetric; lower values of SR have considerably more impact than higher value. This underscores the importance of spawner abundance, as would be expected based on the literature.



1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
64,523,406.17	92,021,829.39	112,609,462.49	120,310,400.62	122,935,345.49

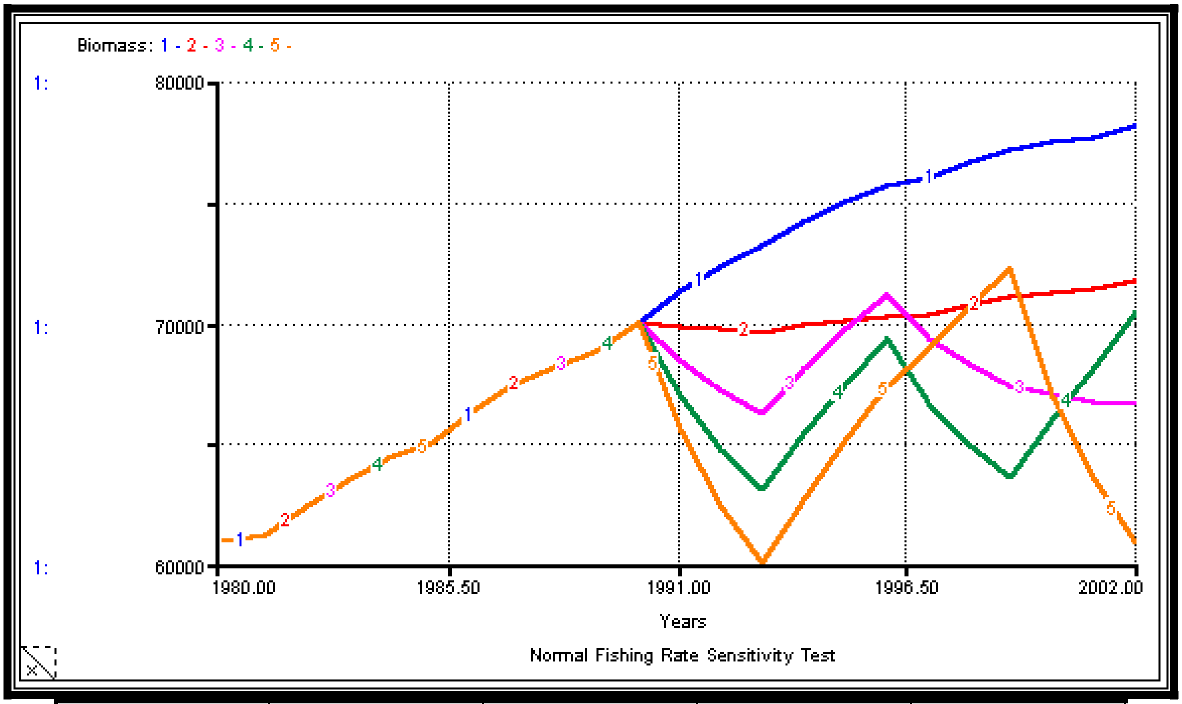
Figure 17– Spawner Rate sensitivity test results

Sensitivity Analysis of *Normal Fishing Rate (NFR)*

Figure 18 shows the sensitivity of the model to varying the *NFR* from .1 to .3. NFR is a fraction that determines what *ABC* will be when fish are plentiful (over 40% of the pristine spawner biomass). Since management wants to keep fish stocks plentiful, *NFR* is clearly an important policy lever. The base run yields the biomass line labeled as 3. The upper values of *NFR* tend to reduce the biomass, which might cause problems for the fishery in the future, whereas lower values result in lower *TGR*. The biomass is very sensitive to changes in NFR. But this is not true for *TGR*, which varies by only a few percent. Also, until the year 1990, biomass is the same in the five different runs because *NFR* does not get activated (due to low spawner biomass levels). After 1990, the effects of varying *NFR* are clearly visible.

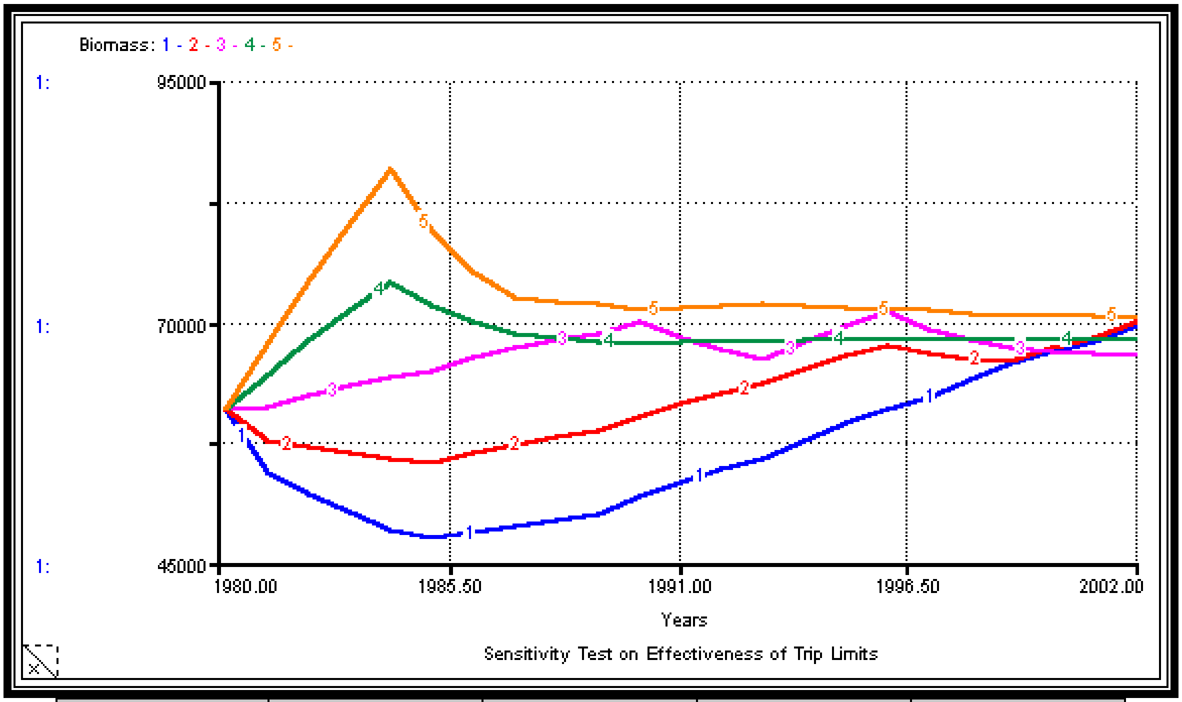
Sensitivity Analysis of *Effectiveness of Trip Limits (ETL)*

Figure 19 indicates that higher values of *ETL* (varying from .36 to 1.1) tend to better sustain the environment. Trip limits are used to regulate fishing, in order to sustain the biomass at a level that will yield maximum harvest without jeopardizing the stock. Total revenues are not greatly affected, due to the fact that the model reduces fishing vessels (overcapacity) over time, irrespective of trip limits. Higher *ETL* values result in better long-term yields from the fishery.



1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
103,887,613.01	109,220,647.52	112,609,462.49	109,954,758.84	115,959,155.47

Figure 18– Normal Fishing Rate sensitivity test results

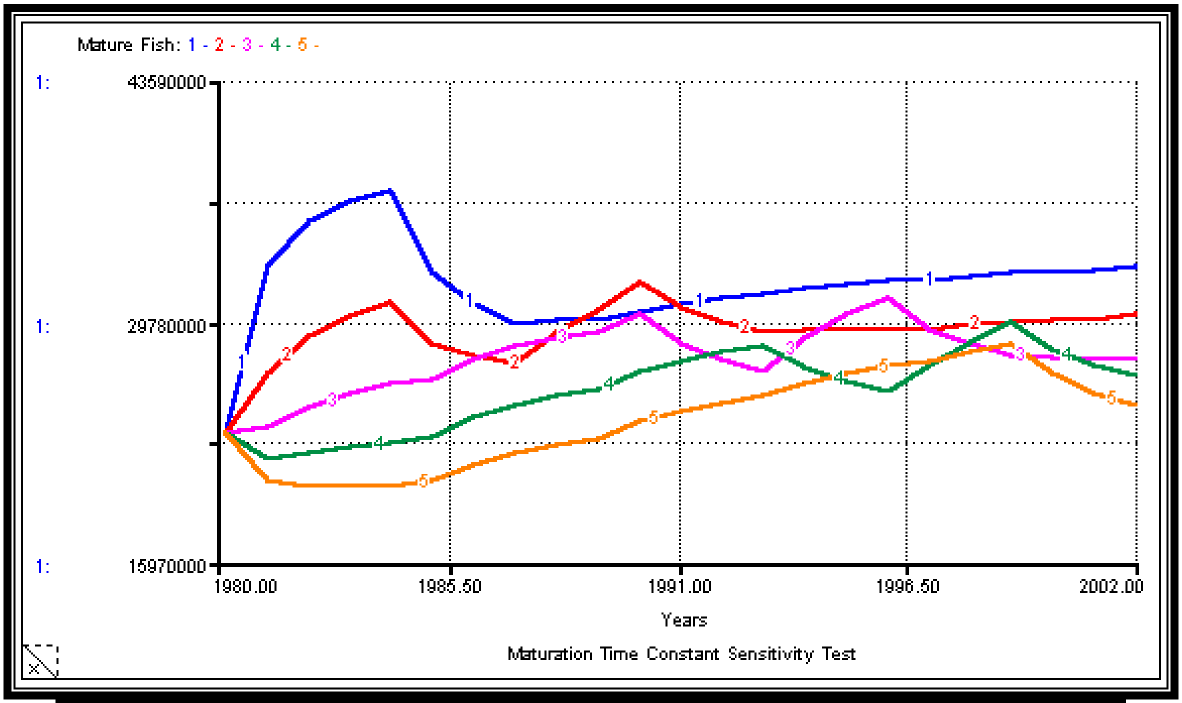


1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
102,612,170.63	107,568,084.38	112,609,462.49	112,325,345.53	110,102,110.15

Figure 19– Sensitivity test results for the Effectiveness of Trip Limits variable

Sensitivity Analysis of *Maturation Time Constant (MTC)*

As shown in Figure 20, varying the *MTC* from 2 to 6 years has a significant impact on *Mature Fish (MF)* population and *TGR*. *MF* is displayed instead of biomass because biomass also includes juveniles. The model is highly sensitive to *MTC*. Shorter *MTC* tends to reinforce *MF* population, yielding higher *TGR*. Higher values of *MTC* result in much lower biomass and *TGR*. These results increase our confidence that the model is behaving in a realistic fashin, and that it possibly could be applied to other fish species. Species such as yelloweye and bocaccio are currently in danger because they have higher *MTC.* Their current stocks of mature fish have been depleted, and it will take many years to rebuild them if fishing is not reduced.

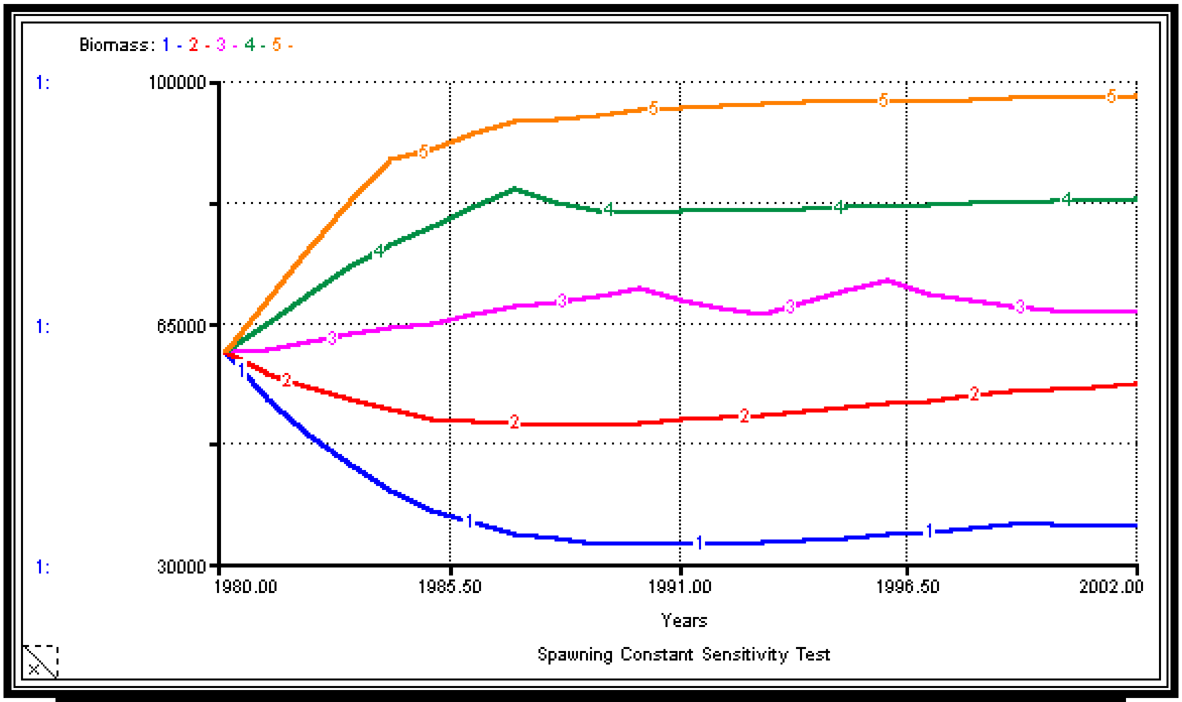


1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
159,615,070.14	132,946,461.63	112,609,462.49	95,255,226.18	82,445,433.41

Figure 20– Maturation Time Constant sensitivity test

Sensitivity Analysis of *Spawning Constant (SC)*

SC is a parameter that regulates the influence of the spawning process, and therefore *Biomass*. We used *SC* to help calibrate the model. Figure 21 shows the model sensitivity to changes in *SC* as it is varied from .12 to .36. *Biomass* seeks a different equilibrium point for each value of *SC,* and the resulting impact on *TGR* is substantial, indicating very high sensitivity to this parameter.



1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue	5: Total Gross Revenue
51,026,707.32	77,472,007.06	112,609,462.49	144,460,725.07	176,829,476.77

Figure 21– Spawning Constant sensitivity test

Table 1 summarizes the results of the sensitivity testing, and Figure 22 displays the information graphically.

	Range (-50%)	Initial Value	Range (+50%)	Total Gross Revenue (TGR) Million $ Base Value = 112 Million $	
				TGR at low value	TGR at high value
Natural Mortality Rate	0.05	0.1	0.15	$132	$ 91
Bycatch Rate	0.06	0.12	0.18	$118	$104
Av. Vessel Capacity (in Tons)	40	80	120	$114	$108
Spawner Rate	0.205	0.41	0.615	$ 65	$123
Normal Fishing Rate	0.105	0.21	0.315	$104	$116
Effectiveness of Trip Limits	0.365	0.73	1.095	$103	$110
Maturation Time Cons. (years)	2	4	6	$160	$ 82
Spawning Cons.	0.12	0.24	0.36	$ 51	$177

Table 1 – Sensitivity Analysis Summary

POLICY ANALYSIS

Several policy questions were studied.

Maximum Sustainable Yield (MSY)

An important aspect of managing a fishery is to determine the proper value for MSY. Without fishing, the biomass will build up to a density that limits fish growth and diminishes the

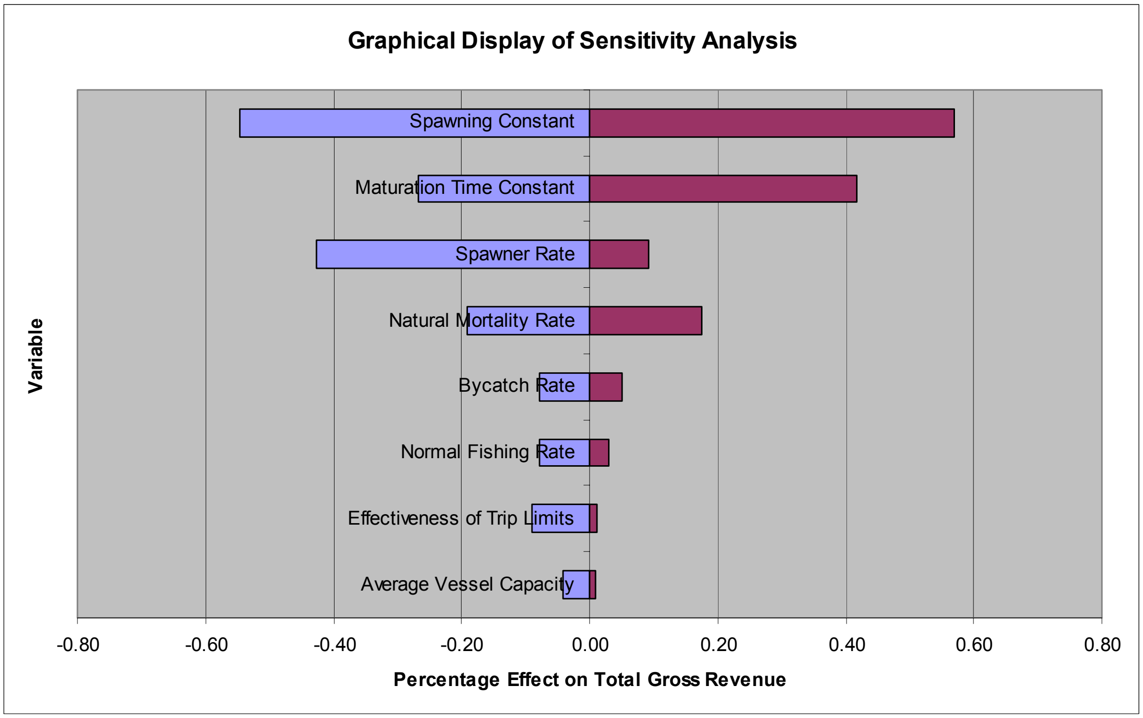


Figure 22–Sensitivity test results portrayed graphically

probability of survival, whereas overfishing will leave few adults to spawn, resulting in a decline of the stock (Watt 1968). The *MSY* lies between these two extremes. We tested five *MSY* values from 30%-50% in intervals of 5%, and obtained the results for *TGR* shown in Table 2.

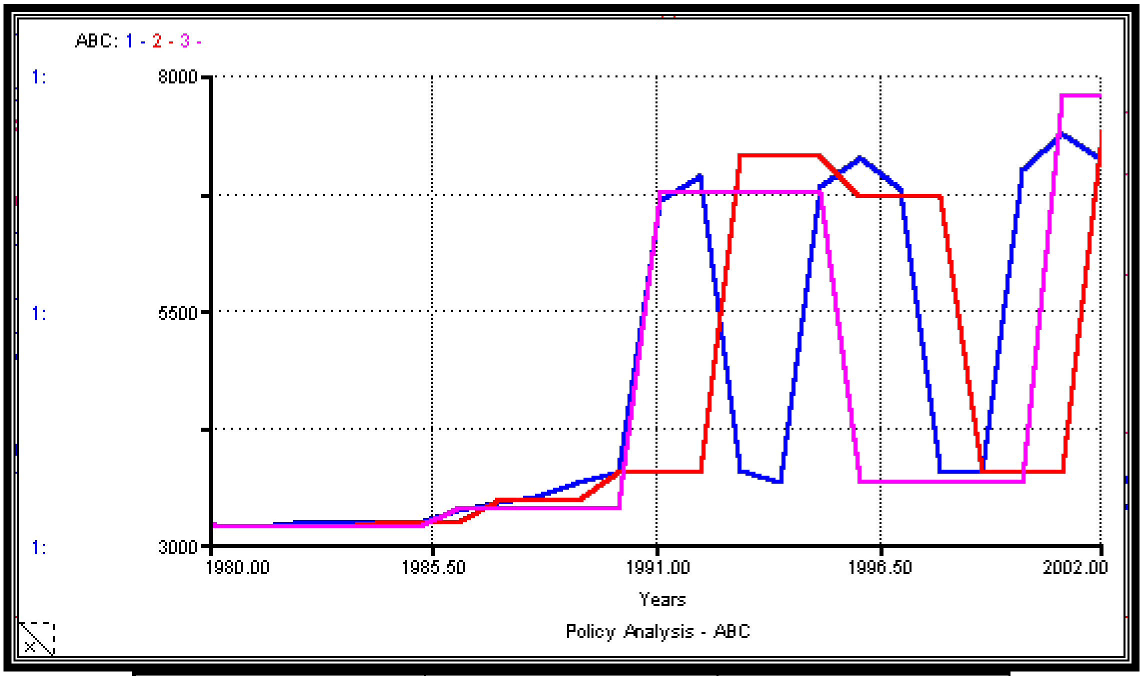
MSY Level	30%	35%	40%	45%	50%
Total Gross Revenue ($)	111,781,268	112,282,020	112,609,462	108,195,051	105,654,051

Table 2: MSY Analysis

When MSY is less than or equal to 40%, *TGR* is approximately the same, but when *MSY* is above 40%, *TGR* decreases. This supports the idea that maximum revenues occur when fish biomass is sustained at 40%, and that *MSY* could possibly be lowered somewhat below 40% without damaging revenues. However, because of the possibility that non-fishing factors may cause major disruptions in fish populations, the PFCC recommends that *MSY* not be lowered below 40%. This is referred to as the “40-10 Policy” in the literature--above 40% is the normal zone; 25%-40% is the precautionary zone; 10%-25% is the protection zone; below 10%, the species faces the possibility of extinction and no fishing is allowed.

***Acceptable Biological Catch (ABC)* Update Frequency**

During model testing, it became clear that another important policy variable is how often the *ABC* value is updated. Consequently, we ran the model with *ABC* being updated every N years (N = 1, 3, 5). Figures 23 and 24 show *ABC* and yellowtail biomass, respectively, for each of these three runs.



1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue
109,338,284.27	106,690,207.66	107,037,329.00

Figure 23– Test of ABC update frequency and its effect on ABC

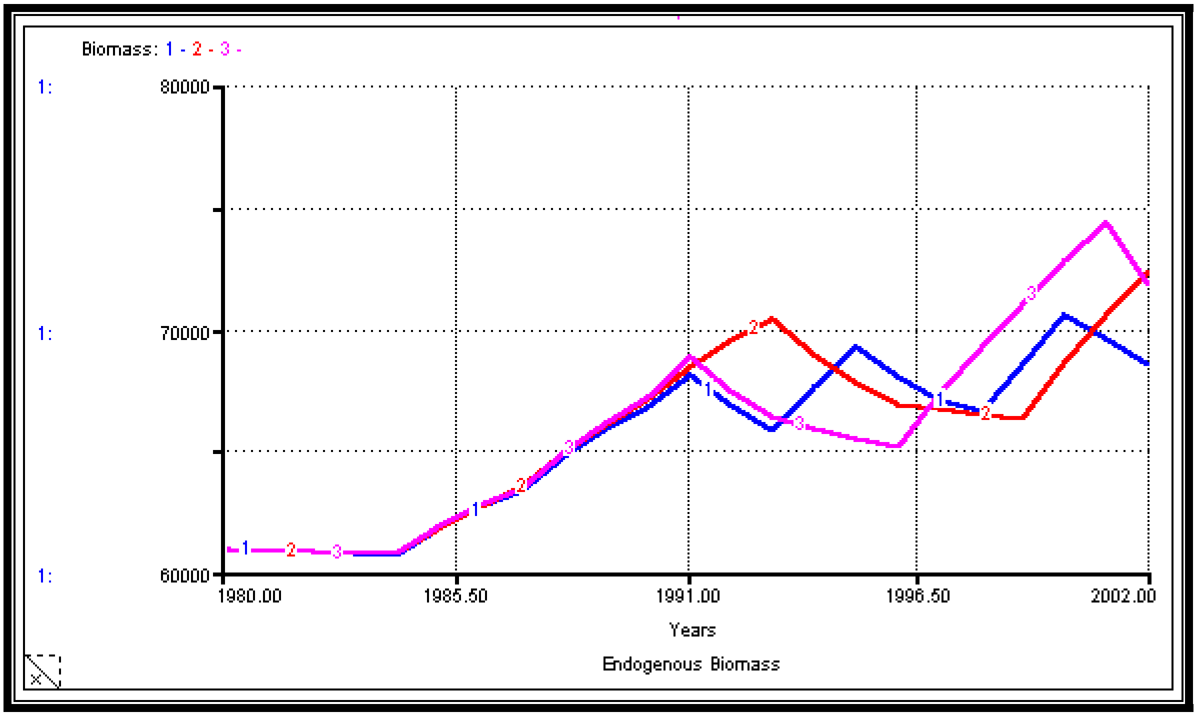
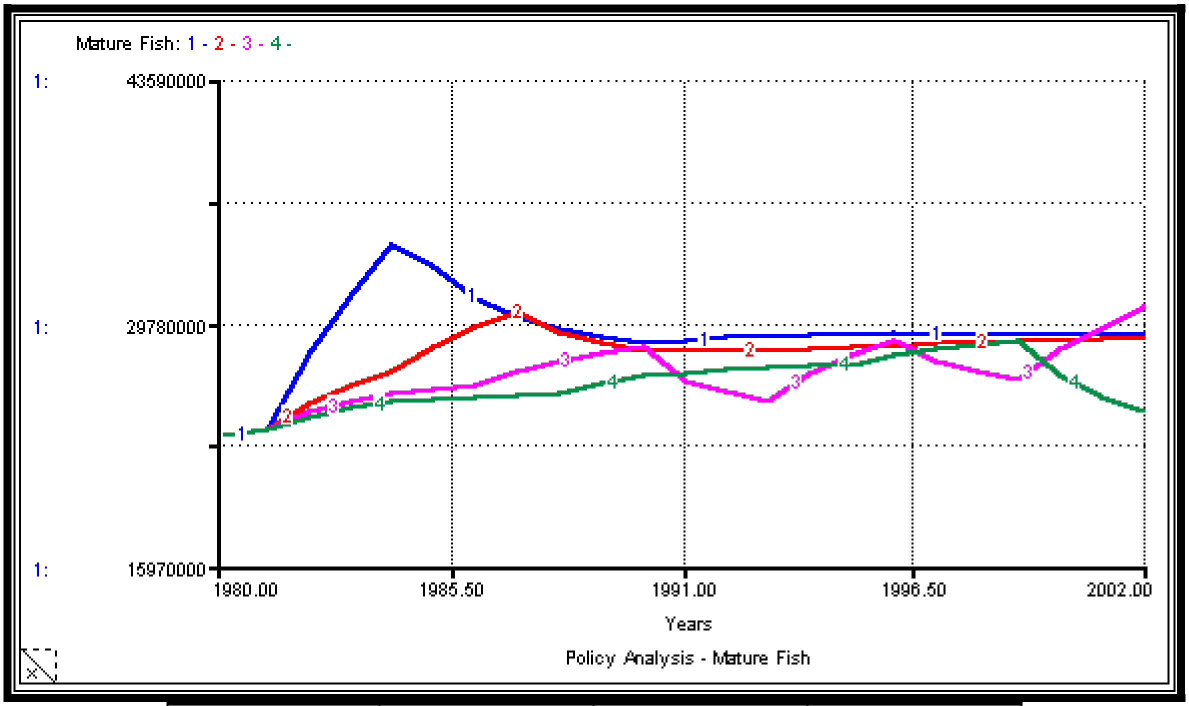


Figure 24 – Test of ABC update frequency and its effect on Biomass

Figures 23 and 24 indicate that increasing the frequency of updates to *ABC* reduces the fluctuations in fish biomass, thereby helping to stabilize the fishery. The graphs are superimposed until 1991, due to the biomass level being at the precautionary zone. After 1991 the fluctuations begin, due to different delay times for updating *ABC*. This result suggests a possible policy for reducing fluctuations in the groundfish fishery. Wide fluctuations may contribute to the ecological and economic decline of the fishery by pushing the biomass towards the protection zone or even extinction.

Management Response Time (MRT)

MRT specifies the time over which imbalances in fishing capacity are rectified, in terms of trawl vessels being removed from the fishery. Figure 25 shows the biomass over time with four *MRT* values, varying from one to seven years in two-year increments.



1: Total Gross Revenue	2: Total Gross Revenue	3: Total Gross Revenue	4: Total Gross Revenue
107,570,454.81	110,037,788.74	111,236,138.18	117,238,053.45

Figure 25 – Biomass for different values of management response time

The lower the *MRT* value, the more quickly *MF* recovers and returns to the *MSY* value, suggesting that *MRT* should be less than five years for best results.

In order to further illustrate how SD models might help analysts and decision-makers explore policy options, a user interface for the model was developed (see Appendix). Additional parameters can be easily varied to simulate different policies, including *Normal Fishing Fraction*, *Precautionary Fishing Fraction*, *Protection Zone Fraction*, and *Effectiveness of Trip Limits*.

Since base model runs show that the present number of trawl vessels focused on yellowtail rockfish is only slightly above the sustainable value, in order to apply the model to evaluate groundfish fleet reductions in a meaningful way, the model would need to be recalibrated using either aggregate groundfish data or data for specific endangered species. Such data has been difficult to obtain.

CONCLUSIONS

Using system dynamics to study the Pacific Coast groundfish fishery was a significant challenge, both in terms of obtaining high-quality data and in terms of specifying and calibrating the model. Despite these challenges, the final model does endogenously reproduce the behavior of fish populations and trawl vessels, two of the most important factors in any fishery model. Endogenously modeling harvest is new to the fishery literature, and we believe that further research in this area is warranted.

Regarding the stability and sustainability of the fishery, the model results suggest that Acceptable Biological Catch (ABC) values should be updated more frequently and that Maximum Sustainable Yield (MSY) should remain at 40%, as stipulated in the Magnuson-Stevenson Fisheries Act. Furthermore, the management response time for fleet reduction should be kept as short as is feasible.

Fishery management requires accurate, frequently updated information about fish populations and socioeconomic data. Ideally, surveys would be done annually and the latest scientific methods would be used to better determine conditions of fish populations. Currently, the National Marine Fisheries Service (NMFS) is increasing the frequency of updating data for some groundfish species, especially those that are considered endangered or at risk. Better and more current information will help to move the Pacific Coast groundfish fishery toward sustainability.

Future Work

Implementing economic and social factors

Further work is needed regarding how to measure the economic impact of the fishery and then determine how changes in harvest would affect social factors. There are several studies in progress that address these issues. However, these studies are not yet able to provide quantitative relationships for community impact.

Incorporating dynamic trip limits

In order to properly determine the harvest endogenously, it will be necessary to model trip limits dynamically, since trip limits are used to implement policy in the actual fishery. Currently, the model uses a non-dynamic trip limit factor. As dynamic trip limits are incorporated, the harvest figures will be closer to the real harvest values, especially in extreme cases such as when the fishery is closed.

Connecting the economic side of the system back to the other aspects of the model

The model is currently generating economic values; however, these values are not fed back to determine the number of trawl vessels that operate, which would in turn impact the harvest and fish population.

Improving how the model incorporates changes in ocean health

Although ocean health is difficult to specify given the data currently at hand, there are obviously connections between ocean health and fish population. More research must be conducted to quantify these relationships so that they can be implemented in the model.

Considering population dynamic models that include the age, size, and weight of fish

Models of fish population used by fisheries biologists are often more complex than our simplified aggregate model. In order to better replicate actual behavior, we may need to utilize the more sophisticated models and data (Tagart 2000).

Incorporating catch per unit efficiency (CPUE) index

Catch per unit efficiency index (Tagart 2000) describes the efficiency of vessels at a given time. It might be helpful to incorporate the CPUE index once the economic and trawl vessel components of the model are connected. Although this index is not as prevalent in the current literature, it was used in early fisheries models and may prove useful to our endeavor.

ACKNOWLEDGEMENTS

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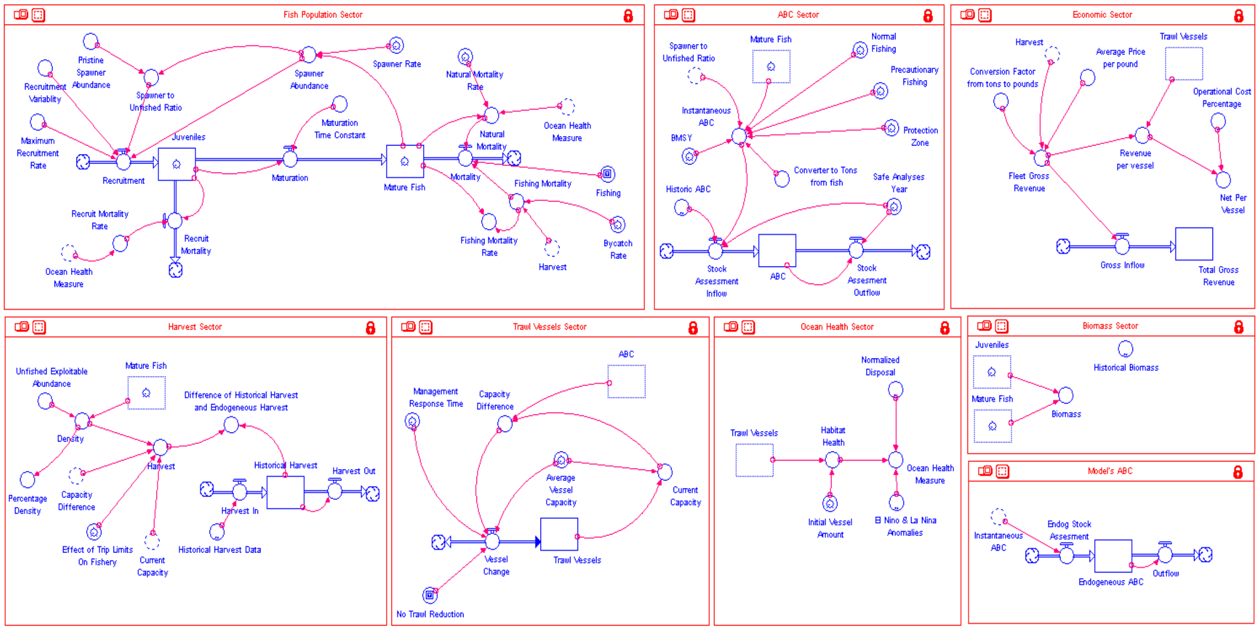
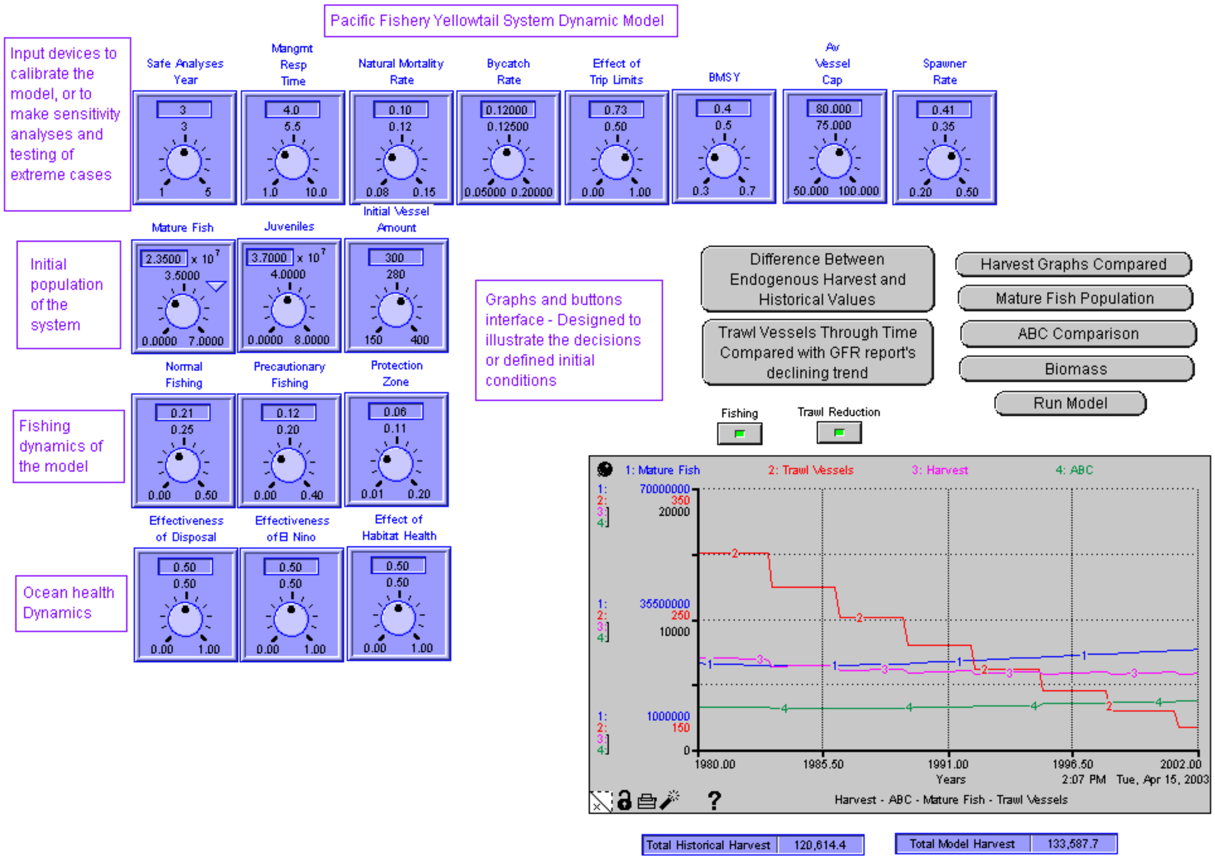
APPENDICES

The model diagram, user interface, equations, and initial value data are provided below.

Model Overview



User Interface



Pacific Fishery Yellowtail System Dynamic Model

Input devices to calibrate the model, or to make sensitivity analyses and testing of extreme cases

Safe Analyses Year: 3
Mangmt Resp Time: 4.0
Natural Mortality Rate: 0.10
Bycatch Rate: 0.12000
Effect of Trip Limits: 0.73
BMSY: 0.4
Av Vessel Cap: 80.000
Spawner Rate: 0.41

Initial population of the system

Mature Fish: 2.3500 x 10^7
Juveniles: 3.7000 x 10^7
Initial Vessel Amount: 300

Fishing dynamics of the model

Normal Fishing: 0.21
Precautionary Fishing: 0.12
Protection Zone: 0.06

Ocean health Dynamics

Effectiveness of Disposal: 0.50
Effectiveness of El Nino: 0.50
Effect of Habitat Health: 0.50

Graphs and buttons interface - Designed to illustrate the decisions or defined initial conditions

Total Historical Harvest: 120,614.4
Total Model Harvest: 133,587.7

Equations

ABC(t) = ABC(t - dt) + (Stock_Assessment_Inflow - Stock_Assesment_Outflow) * dt
INIT ABC = 3200
Stock_Assessment_Inflow = pulse(Instantaneous_ABC,1980,Safe_Analyses_Year)
Stock_Assesment_Outflow = pulse (ABC,1980,Safe_Analyses_Year)
BMSY = 0.4
Converter_to_Tons__from_fish = 1.13/1000
Instantaneous_ABC = (if Spawner_Percentage>BMSY then Normal_Fishing*Mature_Fish else
if Spawner_Percentage>0.25 then Precautionary_Fishing*Mature_Fish else
if Spawner_Percentage>0.1 then Protection_Zone*Mature_Fish else
0)*Converter_to_Tons__from_fish
Normal_Fishing = 0.21
Precautionary_Fishing = 0.12
Protection_Zone = 0.06
Safe_Analyses_Year = 3
Historic_ABC = GRAPH(time)
(1980, 3200), (1981, 3200), (1982, 3200), (1983, 3200), (1984, 3200), (1985, 3000), (1986, 4000), (1987, 4000), (1988, 4000), (1989, 4000), (1990, 4300), (1991, 4300), (1992, 4300),

```
(1993, 4400), (1994, 6740), (1995, 6740), (1996, 6740), (1997, 1773), (1998, 4653), (1999,
3465), (2000, 3539), (2001, 3146), (2002, 3146)
Biomass = (Mature_Fish*1.13+Juveniles*0.93)/1000
Historical_Biomass = GRAPH(time)
(1980, 10785), (1983, 12057), (1986, 9093), (1989, 16861), (1992, 24200), (1995, 2934), (1998,
22614)
Total_Gross__Revenue(t) = Total_Gross__Revenue(t - dt) + (Gross_Inflow) * dt
INIT Total_Gross__Revenue = 0
Gross_Inflow = Fleet_Gross__Revenue
ExVessel_Price = 0.34
Fleet_Gross__Revenue = Harvest*Tons_to_Pounds*ExVessel_Price
Net_Per_Vessel = (1-Operational_Cost_Percentage)*Revenue__per_vessel
Operational_Cost_Percentage = 0.85
Revenue__per_vessel = Fleet_Gross__Revenue/Trawl_Vessels
Tons_to_Pounds = 1000*2.2
Juveniles(t) = Juveniles(t - dt) + (Spawns - Recruitment - Juvenile_Mortality) * dt
INIT Juveniles = 37000000
Spawns=EXP(-
1.73*Spawner_Percentage)*MaximumSpawn_Rate*Spawner_Abundance*Spawning_Variablity
Recruitment = Juveniles/Maturation_Time_Constant
Juvenile_Mortality = Juveniles*Juvenile_Mortality_Rate
Mature_Fish(t) = Mature_Fish(t - dt) + (Recruitment - Mortality) * dt
INIT Mature_Fish = 23500000
Recruitment = Juveniles/Maturation_Time_Constant
Mortality = Fishing_Mortality*Fishing+Natural_Mortality
Bycatch__Rate = 0.12
Fishing = 0
Fishing_Mortality = Harvest*(1+Bycatch__Rate)*1000/1.13
Fishing_Mortality_Rate = Fishing_Mortality/Mature_Fish*1000
Juvenile_Mortality_Rate = 0.2/(Ocean_Health_Measure)
Maturation_Time_Constant = 4
Maximum_Spawn_Rate = 12
Natural_Mortality = (Natural_Mortality__Rate*Mature_Fish)/Ocean_Health_Measure
Natural_Mortality__Rate = 0.10
Pristine_Spawner_Abundance = 32500000/1.13
Spawner_Abundance = Mature_Fish*Spawner_Rate
Spawner_Percentage = Spawner_Abundance/Pristine_Spawner_Abundance
Spawner_Rate = 0.41
Spawning_Variablity = 0.24
Historical_Harvest(t) = Historical_Harvest(t - dt) + (Harvest_In - Harvest_Out) * dt
INIT Historical_Harvest = 0
Harvest_In = PULSE(Historical_Harvest_Data,0,1)
Harvest_Out = PULSE(Historical_Harvest,1,1)
Density = Mature_to_Unfished_Ratio/Fish_Density_Coefficent
Difference_of_Historical_Harvest_and_Endogeneous_Harvest = Harvest-Historical_Harvest
Effect_of_Trip_Limits = 0.73
```

```
Fish_Density_Coefficent = 0.4
Harvest = (Current_Capacity-Restrictions)*Density
Mature_to_Unfished_Ratio = (Mature_Fish/Unfished_Exploitable_Abundance)
Percentage_Density = Mature_to_Unfished_Ratio*100
Restrictions = (Capacity_Diff*Effect_of_Trip_Limits)
Unfished_Exploitable_Abundance = 74000000
Historical_Harvest_Data = GRAPH(Time)
(1980, 8664), (1981, 9184), (1982, 9185), (1983, 9500), (1984, 5393), (1985, 3830), (1986,
3478), (1987, 5785), (1988, 6670), (1989, 5046), (1990, 4754), (1991, 4273), (1992, 6822),
(1993, 5861), (1994, 6456), (1995, 6069), (1996, 6344), (1997, 2323), (1998, 3144), (1999,
3598), (2000, 3539), (2001, 3146), (2002, 2540)
Endogeneous_ABC(t) = Endogeneous_ABC(t - dt) + (Endog_Stock__Assesment - Outflow) * dt
INIT Endogeneous_ABC = 0
Endog_Stock__Assesment = pulse((Instantaneous_ABC),0,1)
Outflow = pulse (Endogeneous_ABC,3,1)
Disposal_Effect = Effectiveness_of_Disposal*Disposal_Condition
Effectiveness_of_Disposal = 0.5
Effectiveness__ofEl_Nino = 0.5
Effect_of_Habitat_Health = 0.5
El_Nino_Effect = Effectiveness__ofEl_Nino*El_Nino_Anomalies
Habitat_Health = Effect_of_Habitat_Health*Habitat__Condition
Habitat__Condition = 1-(Trawl_Vessels/Initial_Vessel__Amount)
Initial_Vessel__Amount = 300
Ocean_Health_Measure = 1-Disposal_Effect*Habitat_Health*El_Nino_Effect
Disposal_Condition = GRAPH(time)
(0.00, 0.982), (1.00, 0.961), (2.00, 0.968), (3.00, 0.963), (4.00, 0.912), (5.00, 0.931), (6.00,
0.936), (7.00, 0.948), (8.00, 0.949), (9.00, 0.948), (10.0, 0.9), (11.0, 0.969), (12.0, 1.00), (13.0,
0.956), (14.0, 0.974), (15.0, 0.965), (16.0, 0.999), (17.0, 0.948), (18.0, 0.904), (19.0, 0.938),
(20.0, 0.999)
El_Nino_Anomalies = GRAPH(time)
(0.00, 0.95), (2.00, 0.855), (4.00, 0.96), (6.00, 0.975), (8.00, 0.96), (10.0, 0.9), (12.0, 0.88), (14.0,
0.8), (16.0, 0.95), (18.0, 0.95), (20.0, 0.905)
Trawl_Vessels(t) = Trawl_Vessels(t - dt) + (- Vessel_Change) * dt
INIT Trawl_Vessels = Initial_Vessel__Amount
Vessel_Change=
INT(pulse((Capacity_Diff/Av_Vessel_Cap)/(Mangmt_Resp_Time),1983,3)*Trawl_Reduction)
Av_Vessel_Cap = 80
Capacity_Diff = (Current_Capacity-ABC)
Current_Capacity = Av_Vessel_Cap*Trawl_Vessels
Mangmt_Resp_Time = 4
Trawl_Reduction = 0
Total_Historical_Harvest(t) = Total_Historical_Harvest(t - dt) + (Noname_2) * dt
INIT Total_Historical_Harvest = 0
Noname_2 = Historical_Harvest_Data
Total_Model_Harvest(t) = Total_Model_Harvest(t - dt) + (Noname_4) * dt
INIT Total_Model_Harvest = 0
```

Noname_4 = Harvest
Normal_Level = 40
Precautionary_Level = 25
Protection_Level = 10
X_Axis=0

Initial Values

- **Average Vessel Capacity:** Average capacity in metric tons per vessel per year. We assumed an average capacity around 80 mt, which is an approximation derived from the PFMC Science and Statistics Committee capacity calculation - SSC Economics Subcommittee (2000) (PMCC & Ecotrust 2002).
- **ExVessel Price:** Calculated as $0.34 per pound according to the historical data (PFMC 1981:2003).
- **B_{MSY}:** Maximum sustainable yield is set to 40% of the biomass according to research literature. In fact, the federal harvest regime dedicates this exploitation rate, and the regime is explained in most groundfish harvest regulation reports (PFMC 2000; NOAA 1996).
- **Bycatch Rate:** This is assumed by the Pacific Council to be 16% of the fish harvested (PFMC 1981:2003).
- **Initial Vessel Amount:** Assumed as 20% of the total trawl vessels working in the groundfish area in year 1980.
- **Juveniles:** Estimated to be 37 million juveniles.
- **Management Response Time:** The time it takes the system to respond to imbalances in overall vessel capacity. Assumed to be 4 years.
- **Maturation Time Constant:** It takes 4 years for yellowtail juveniles to mature into adults (Tagart et al. 2000).
- **Mature Fish:** Estimated to be 23.5 million fish.
- **Maximum Spawn Rate:** This is set to 12 fish per year for each spawner on average.
- **Natural Mortality Rate:** 11% of the exploitable biomass (Tagart et al. 2000).
- **Pristine Spawner Abundance:** 32,500mt that or about $2.8x10^7$ spawner fish (Tagart et al. 2000).
- **Pristine Exploitable Abundance:** The biomass is estimated around 114,700 mt for yellowtail which means the exploitable biomass is around 74 million fish assuming a linear relationship between biomass and mature fish (Tagart et al. 2000).
- **Spawning Variability:** This is set to 0.24 initially to give a mean spawning value of 14 million fish per year (Tagart et al. 2000).
- **Spawner Rate:** Calculated through the relationship between spawner and exploitable biomass, using the algorithm described in the Yellowtail Rockfish Report 2000 (Tagart et al. 2000). It averages 0.3857 of the exploitable biomass.

Definitions of Variables in Fish Population Sector

- **Mature Fish**: Also called exploitable abundance. This is the stock of mature fish at any given time.
- **Juveniles**: Stock of juveniles at any given time.

- **Maturation Time Constant (MTC):** The time it takes juveniles to become mature fish. This varies from species to species. For yellowtail, it takes an average of 4 years for a juvenile to become a mature fish.
- **Natural Mortality Rate (NMR)**: Average annual natural mortality fraction for mature yellowtail.
- **Natural Mortality:** The product of NMR and the mature fish.
- **Fishing Mortality:** Fish caught by trawl vessels and bycatch.
- **Mortality**: Sum of natural mortality and the fishing mortality.
- **Spawner Percentage:** Ratio of spawner abundance to the pristine spawner abundance.
- **Spawner Abundance:** The number of fish that participate in the spawning process.
- **Pristine Spawner Abundance**: The average number of spawners when no fishing occurs for a long period of time.
- **Maximum Spawning Rate:** Maximum juveniles from one mature female fish.
- **Spawning Variability:** Models degree of variance in juveniles, according to historical data.
- **Spawns:** The amount of newborn fish added each year to the juvenile stock.
- **Juvenile Mortality Rate:** Annual fraction of the juvenile stock that flows out due to natural mortality.
- **Juvenile Mortality:** The product of juvenile mortality rate and juveniles.

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