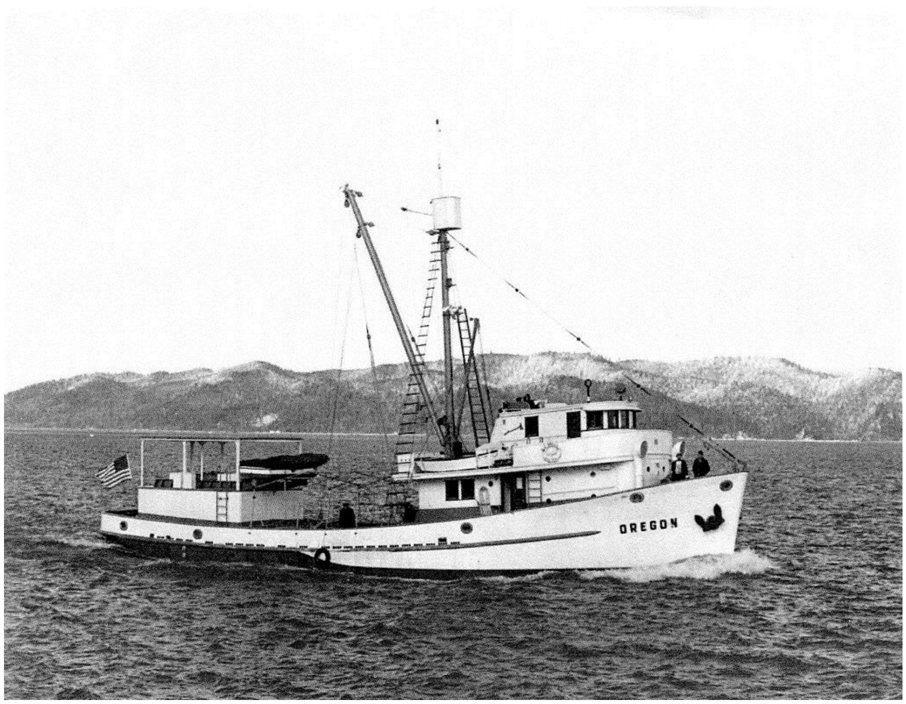
EXERCISE TWO

COASTAL FISHERIES



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Submitted on 2/13/16
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Problem Formulation

The primary goal of this modeling exercise was to develop and calibrate a model to represent a coastal fishery. A fishery is generally defined in terms of the "people involved, species or type of fish, area of water or seabed, method of fishing, class of boats, [the] purpose of the activities or a combination of the foregoing features."

For this modeling exercise, the system has been simplified to exclude key factors influencing fish population and harvest such as juvenile fish, the relationship between fish harvest and price per fish, expected changes over time in vessel outfitting cost, regulatory limitations to harvest, ongoing maintenance costs, and the like

A key concept is the relationship between ecological carrying capacity and fish populations. Carrying capacity can be defined as “the maximum population size of the species that the environment can sustain indefinitely, given the food, habitat, water, and other necessities available in the environment.” As the population of a given species approaches the carrying capacity, competition for resources generally results in higher mortality and lower reproduction rates. From a systems dynamics perspective, this relationship constitutes a balancing feedback process that stabilizes the population.

In this exercise, a key point of emphasis was the calibration of the model to approximate a reference behavior pattern (RBP) provided in the project specifications. The RBP was described as a “straight line for vessels and fish. Additionally, although not specified in text, it is assumed that the RBP should not only be straight, but should have a slope approaching zero once the model reaches equilibrium.

Consideration of the RBP description raises the obvious question of how to determine an appropriate level of calibration (from both a qualitative and quantitative standpoint). For the purposes of this exercise, the author has elected to evaluate correspondence with the RBP using the following three measures:

1. Visual correspondence to a flat line (i.e. the “eyeball test”).
2. The change in value from the first time step to the last time step.
3. The standard deviation of the values across all time steps.

Model Development

Model development began with the development of a Stock and Flow Diagram (SFD). As has been discussed in course lectures, in situations where the modeling effort begins with a clear understanding of the system (including equations and starting values), it is often easiest to begin with a SFD rather than a Closed Loop Diagram (CLD).

The model was developed using three co-flows: 1) fish populations (unit = fish), 2) income related to fish harvest (unit = dollars), 3) fleet of fishing vessels (unit = fishing boats). Model components are described below, and are shown graphically in the figure that follows.

Stock variables representing the total fish population, fish caught, total profit generated, and the number of fishing vessels in the fleet include the following:

- Fish (co-flow 1) = INTEG(Reproducing-Harvesting-Dying) [*Initial value = 5E6*]
- Catch (co-flow 1) = INTEG(Harvesting) [*Initial value = 0*]
- Profit (co-flow 2) = INTEG(Income) [*Initial value = 0*]
- Fishing Vessels (co-flow 3) = INTEG(Outfitting-Senescing) [*Initial value = 50*]

Flow variables representing fish birth, death, and harvest, vessel outfitting and senescence, and income generation include the following:

- Reproducing (co-flow 1) = Fish*Birth constant/Population density
- Harvesting (co-flow 1) = Population density*Max yield*Vessels
- Dying (co-flow 1) = Death constant*Fish*Population density
- Income (co-flow 3) = Harvesting*Profit per fish
- Outfitting (co-flow 3) = ROI Constant*Vessel lifetime*Income per vessel/Vessel cost
- Senescing (co-flow 3) = Vessels/Vessel lifetime

Auxiliary variables, including the values obtained from the calibration described below, include the following:

- Carrying capacity = 10,000,000
- Population Density = Fish/Carrying Capacity
- Birth constant = 0.385
- Death constant = 1.0
- Profit per fish = $2
- Cost per vessel = $210,000
- Vessel lifetime = 20 years
- ROI Constant = 0.5
- Income per vessel = Income/Vessels
- Max yield (defined as the maximum number of fish harvested per year per vessel when population density is equal to one) = 50,000

Note that there are three constants added to the model: birth, death, and ROI. The first two are used solely for calibration purposes, and serve to quantify the proportional dependence of birth and death on carrying capacity. As such their values are determined empirically by matching the RBP. The ROI constant however serves to relate the number of vessels outfitted per year to income per vessel. Outfitting should be proportional to the expected profit given the lifetime of a vessel. An ROI constant of one means that one vessel will be created per year when the expected total profit across the lifetime of the boat will be equal to the cost of a new vessel. Obviously, simply recouping one’s investment in a vessel would not cover additional expenses such as labor and fuel. As such, a simplifying assumption was made that expected profit should be double the cost of a new vessels, which is equivalent to an ROI constant of 0.5.

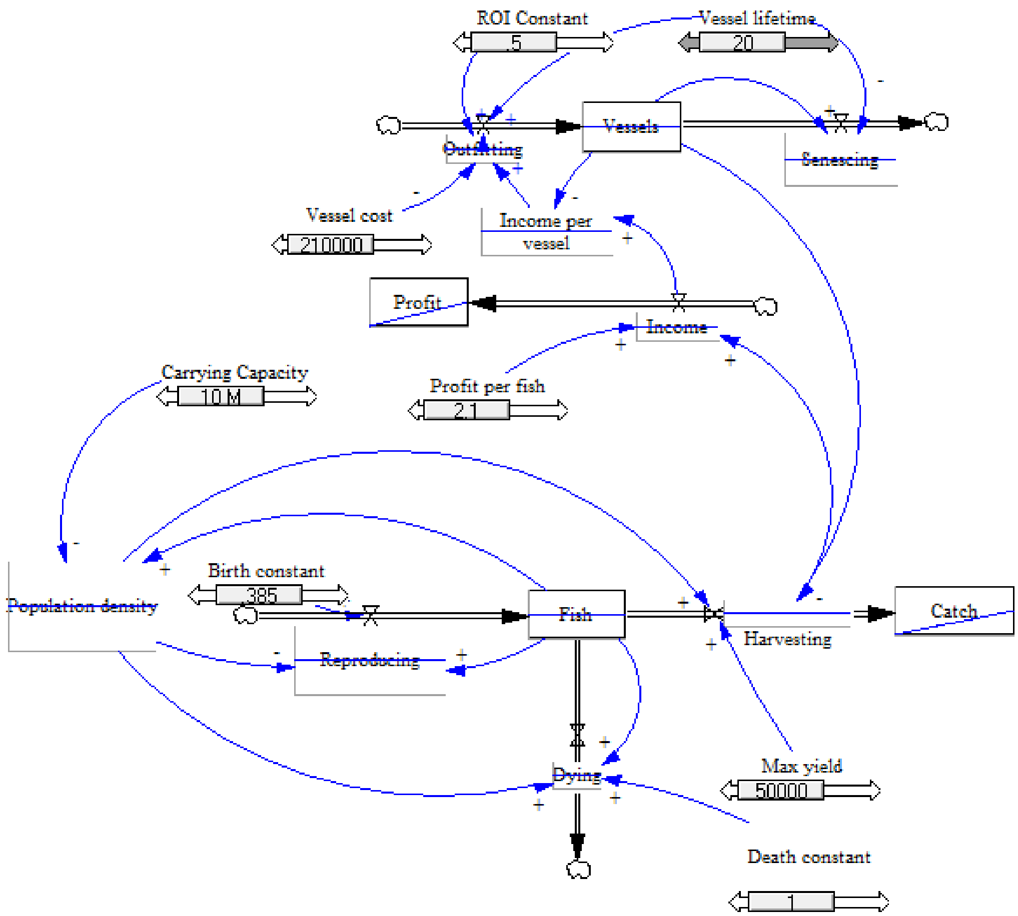

Figure 1. Calibrated SFD

Model Testing & Calibration

The primary goal of model testing and calibration was to reproduce the RBP described above. Starting values were obtained from the project specifications, and used as a "point of departure" for calibrating the model output. A primary challenge encountered was to calibrate the model within the relatively open project specifications, the graphical RBPs provided, and the lack of prescribed targets for the precision of the calibration. This was particularly challenging when attempting to recreate the RBP for the first few time steps.

It is expected that when developing a real world model for practical application, parameter values might be constrained by a range of possibilities as determined by real world data. For example, the prices and lifetimes of different types of fishing vessels could be used to set and upper and lower boundary for their respective parameters. However as this exercise lacks the specificity needed to set those boundaries and the project specifications explicitly state that the provided values are simply "starting points", primary consideration was given to reproducing the RBP.

The Synthesim tool was used to systematically adjust variables as needed to match the RBP. Although model output under various scenarios will be discussed in detail in the Results section of this document, it is worth noting that it was relatively easy to generate model output that asymptotically approaches a straight line (thus emphasizing the power of the balancing feedback loops in the system). It was more challenging to minimize the amount of model "burn in" and by extension the deviation between model equilibrium and starting values.

The model output was analyzed to address the two quantitative tests of correspondence with the RBP (note that for analytical convenience this was calculated with a time step of one). As one can see in the table below, 1) the total percent change is less than 2% for both stocks (across one hundred years), indicating that there is no substantial cumulative change across the model run and 2) the standard deviation relative to the starting value is well less than 1%, indicating that there is very little jitter across time steps.

Table 1. Calibration Metrics

Metric	Fish	Vessels
Starting Value (SV)	5000000	50
Final Value	5066257	50.66
Total Change	66257	0.66
%Change	1.33%	1.32%
Standard Deviation (SD)	8100	0.17
SD/SV(as %)	0.16%	0.33%

The results of the tests described above indicate that the model was adequately calibrated relative to the RBP, and is suitable for further experimentation and analysis as described below.

Finally, the appropriateness of the initially selected time step (set at 1) was tested by lowering the step to 0.0625 and comparing the output. The output matches closely at a gross level but has noticeable discrepancies during the early "burn in" phase as shown below. As such the time step was adjusted to 0.0625 for subsequent modeling and analysis.

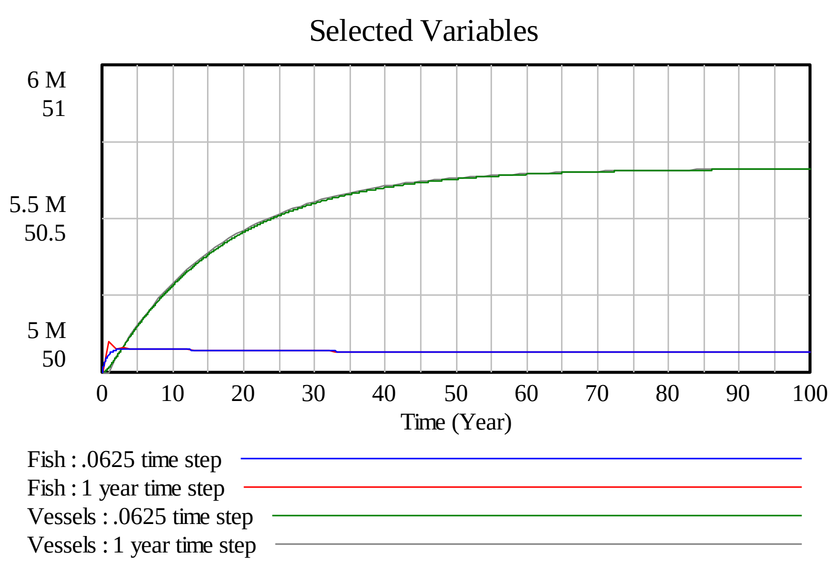

Figure 2. Effect of decreasing the time step

Model Application

The model as described provides a simplistic framework for evaluating the relationships between carrying capacity, fish populations, and harvesting. However the absence of numerous key variables which impact fish populations and the economics of harvest substantially limit the applicability of this model. Potential improvements which could address these limitations are discussed at the close of this document. From a methodological standpoint, the use of quantitative estimates of correspondence to the RBP are widely applicable to future modeling efforts, and represent an area the author found most interesting and useful.

Results & Conclusions

Feedback Loops

The model contains multiple feedback loops that serve to regulate the system and drive it towards dynamic equilibrium. Population density (K) serves stabilize population numbers by increasing death, harvest and reproduction. Increases in population further increase death, reproduction and harvest. Increased vessel numbers are balanced by a decrease in 1) available fish to harvest as the number of vessels increases, thus lowering total income and 2) a decrease in income per vessel as the number of vessels increases.

Initial Vessel/Fish Increase of 50%

The fully calibrated model was first manipulated by increasing the initial number of vessels by 50%. The results are presented below and qualitatively match those presented in the "Sample RBP" shown in the exercise specifications. One can clearly see that the number of vessels decays exponentially towards equilibrium (~50), whereas the number of fish dips initially (due to the many vessels harvesting) and then rises gradually back to its equilibrium value.

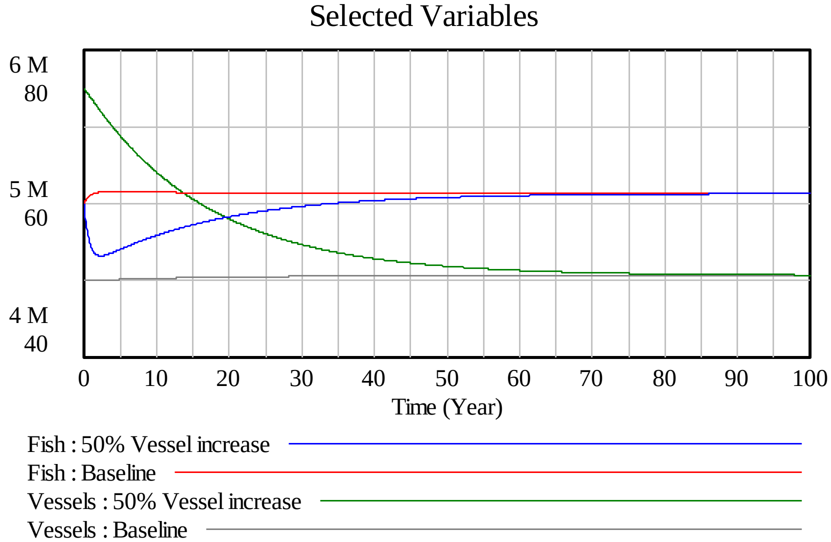

Figure 3. Effect of a 50% initial increase in vessels

The figure below illustrates the feedback that is driving the dynamics of the system during this manipulation. As one can see, in the early stages of the simulation, even though the total profit is much higher than baseline (due to more harvest), the profit per boat is much lower as a result of the greater number of vessels. This in turn results in less vessels being outfitted, balancing the system and pushing it back towards equilibrium. Because of the long delay associated with senescence (i.e. only 5% of boats per year senesce), it takes many decades for the number of vessels (and by extension fish) to return to baseline conditions.

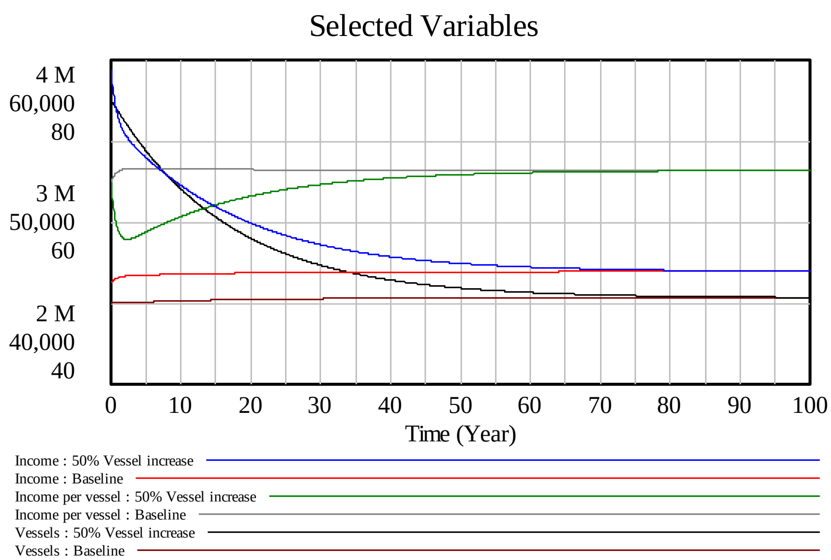

Figure 4. Effect of a 50% initial increase in vessels on income

When the starting population of fish was increased by 50% instead (i.e. with vessels at baseline of 50), the fish population drops dramatically and rapidly back towards the systems equilibrium value of ~5 million in tandem with harvesting and dying. The return to equilibrium happens so quickly that there is not enough time for the number of vessels to grow substantially. This finding emphasizes the differences between the fish and the fleet co-flows in the speed of their response.

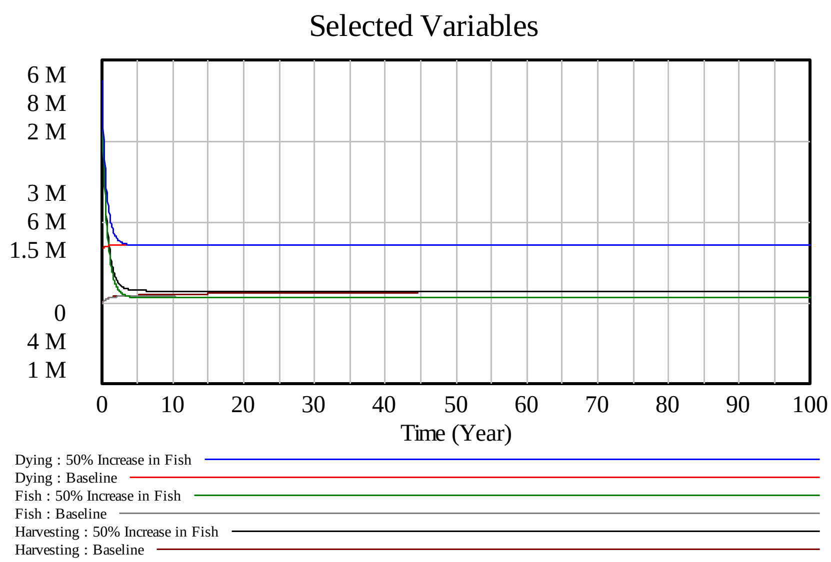

Figure 5. Effect of a 50% initial increase in fish on the fish co-flow

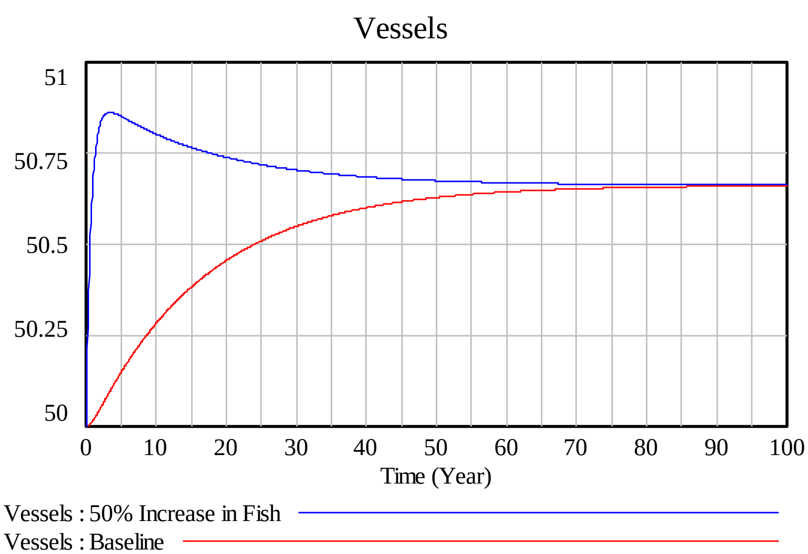

Figure 6. Effect of a 50% initial increase in fish on vessels

Increasing K, Profit per Fish, and Maximum Yield

K, profit per fish, and maximum yield were all doubled (independently of one another) to explore the effects on the system. As one can see below, doubling K results in a rapid increase in fish numbers and a slow increase in vessels.

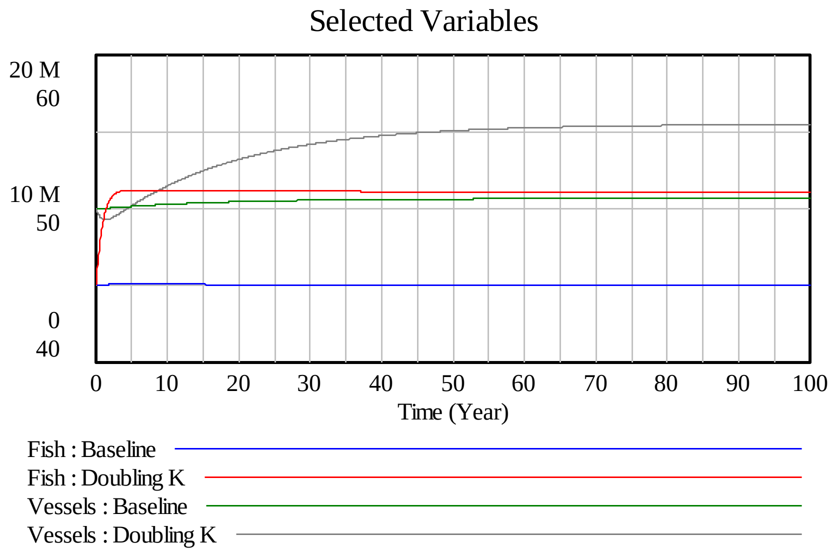

Figure 7. Effect of doubling K on vessels and fish

A surprising result is that doubling K results in an initial dip in vessel numbers. Further inspection of the model output shows that doubling K lowers the population density, and because harvest *is arbitrarily defined in terms of population density rather than areal density*, the model shows an initial drop in harvest numbers which propagate onwards to outfitting and vessel numbers. This result does not make intuitive sense, and emphasizes the unexpected and often unpredictable impacts of incorrectly modeling a system. Improvements to the model which could address this issue are discussed below.

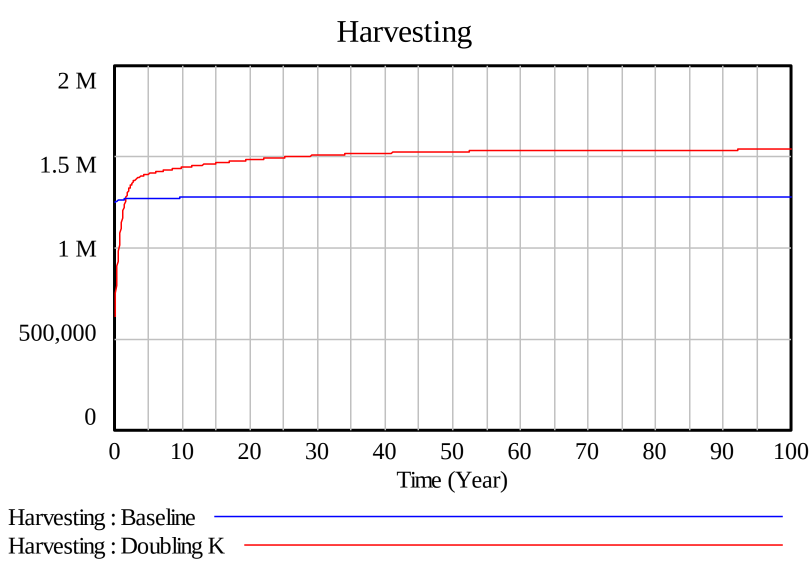

Figure 8. Effect of doubling K on harvesting

Doubling profit per fish results in higher equilibrium values for vessels and lower values for fish. In contrast to doubling K however (which effects change principally through the fish co-flow), doubling profit per fish impacts the fish numbers slowly and in concert with changes to vessel numbers. This finding emphasizes the different temporal dynamics of these components of the system.

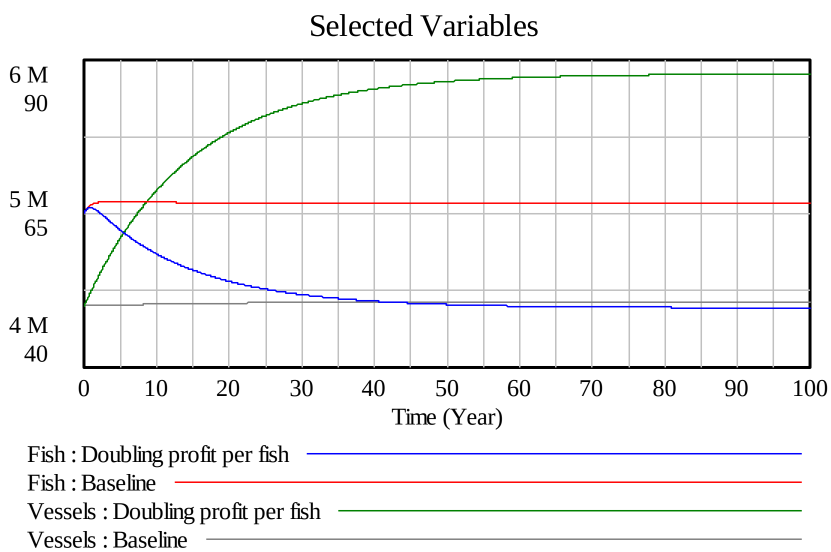

Figure 9. Effect of doubling profit per fish on vessels and fish

Doubling maximum yield generates a pattern qualitatively very similar to doubling profit per fish. This is intuitively logical as both increase the number of vessels by increasing profit per vessel. Increasing maximum yield however results in a greater decrease in the equilibrium value of fish.

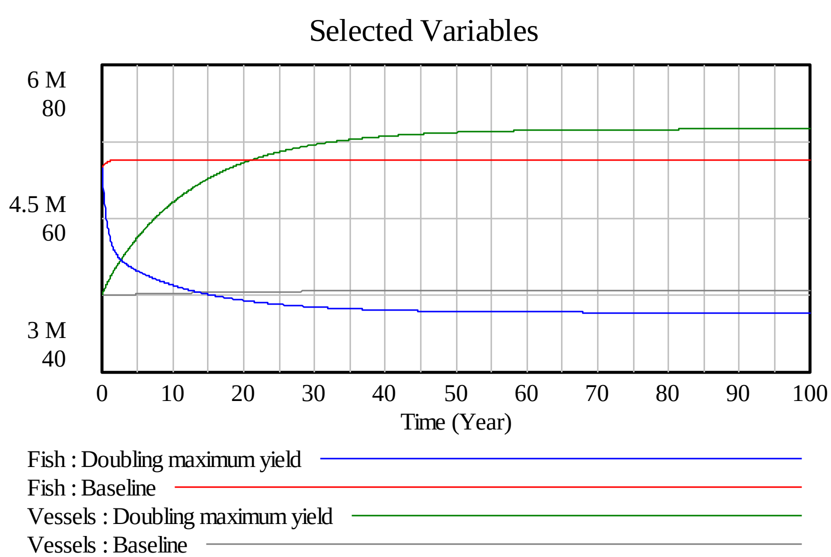

Figure 10. Effect of maximum yield per fish on vessels and fish

Linear Decay of Carrying Capacity and Subsidizing Vessel Outfitting

In this manipulation, the carrying capacity was first set to decay in a linear fashion to half its value at 50 years (and by extension to zero at 100 years). This was accomplished by setting up a shadow variable for TIME, and calculating carrying capacity (K) at each time step as equal to 1e+007-(100000*Time). Subsequently, a "subsidy" was added which decreased the cost to outfit a vessel at Year 5 by 50%. This was accomplished by changing the Vessel cost variable as equal to 210000-STEP(105000,5).

As can be seen in the figure below, decreasing carrying capacity unsurprisingly drives the number of fish and vessels downwards in a proportional manner. Adding the subsidy results in a large jump in vessels at the time it is implemented, followed by a slow decrease. Furthermore, the results suggest that carrying capacity is the primary driver of fish numbers as one can see that even when the number of vessels (and by extension harvest pressure) is increased substantially under the subsidy, there is only a small decrease in the fish population. When the vessel cost is decreased without the decay in carrying capacity, fish populations decline towards a new equilibrium value, further emphasizing that carrying capacity is a key stabilizing force in this system.

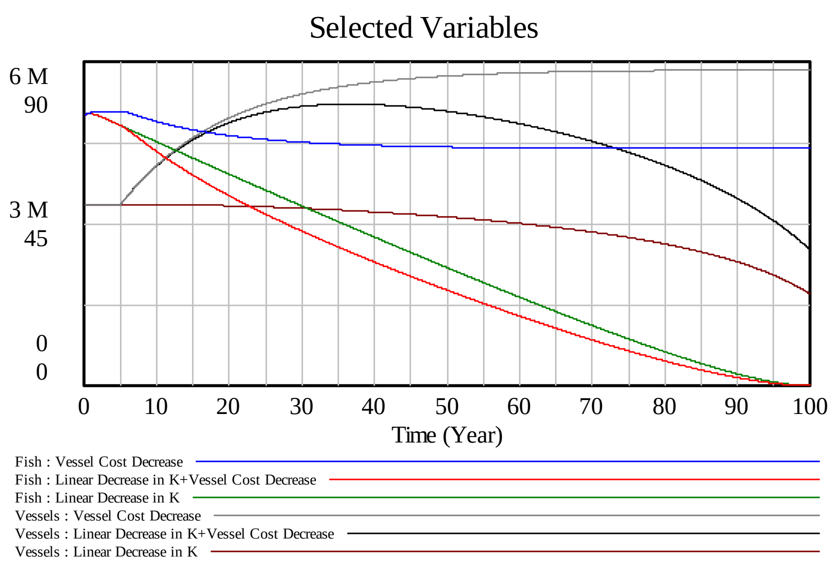

Figure 11. Effects of decaying K and vessel subsidies

Summary of Conclusions

The results of the manipulations show that the system has a powerful tendency towards a dynamic equilibrium between fish and vessels. One-time changes to model variables invariably pushed the system to new but repeatable equilibrium values. The time required to find a new equilibrium was dependent on where the change occurred. Changes to the vessel or income co-flow caused slow changes related to the delays introduced by the outfitting and senescing rates; changes to fish co-flow showed rapid responses in equilibrium values. Finally, monotonic and ongoing decreases to carrying capacity push the system out of equilibrium, resulting in a decrease to zero in population values. Unfortunately this scenario matches the current state of the world where factors such as global warming and habitat loss are persistently degrading the carrying capacity of our oceans.

Potential Model Improvements

As discussed above, numerous simplifying assumptions were made to 1) accommodate the time available to complete this exercise, and 2) to facilitate the process of model calibration (which was a primary focus of this exercise). As such, the model does not reflect key features of a real world fishery. Real world fisheries are influenced by myriad ecological, regulatory, and economic factors far beyond the scope of this exercise. A decidedly incomplete discussion of areas of potential improvement and model expansion are described below.

- *Juvenile fish* were not disaggregated from adult fish in the model. An early attempt to include them was scrapped to simplify the model calibration. However juvenile fish could reasonably be incorporated as an additional stock as part of an aging chain. However their introduction requires consideration of how juveniles impact the population density (i.e. one juvenile fish does not equal one adult fish), and what the impacts of harvest are to their population (i.e. intentional juvenile catch is generally not legal but they do comprise a portion of the accidental bycatch).
- *Profit per fish* is, in the real world, driven by a combination of supply and demand. Intuitively it is clear that increased harvest within the fishery modeled would decrease supply and therefore increase price. However supply is dependent on a complex relationship between the aggregate (i.e. multiple fisheries including those outside this model) of all harvested fish and logistical issues related to transportation to a given market. As such, there is no straightforward way to incorporate this feedback loop without substantially expanding the scope of the model. Another potential solution would be to feed in real world time series data of prices to improve the accuracy of the model. This approach would likely sacrifice interpretability of the results in exchange for better model fit however. Another way to approximate changes in price would be to introduce synthetic noise to the profit per fish variable.
- *Vessel maintenance* constitutes an ongoing expense for vessel operators, and may increase with both the age of the vessel and the total amount of harvesting.
- *Labor constraints* (i.e. a limited pool of available workers) may cap the number of total vessels in the fleet, and as the system approaches that cap, labor costs may increase, thereby balancing the outfitting of new vessels.
- *Regulatory decisions* can have dramatic impacts on fisheries. For example, designation of a given species as Threatened or Endangered can suspend all or most of the harvest operations. Safety regulations may increase the cost to operate a vessel. Trade agreements may open up new markets however, leading to higher profit per fish.
- *Areal density dependence of harvest* is approximated in the model prepared for this exercise using population density (population to carrying capacity ratio). However a more accurate way to calculate harvesting rates would be to use fish per square (or cube depending on the harvest technique) unit of length (e.g. meters).

References

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3. **Wikipedia**. https://en.wikipedia.org/wiki/Fishery