Using Interactive Visualization to Enhance Understanding of a Fisheries Model

BY

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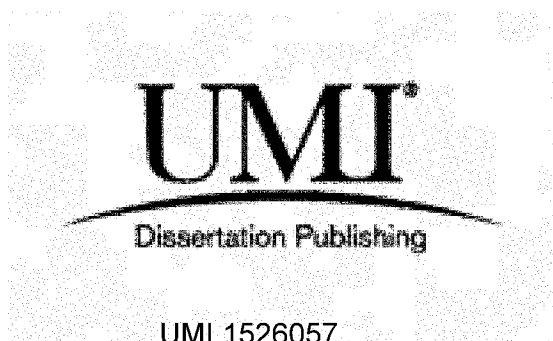
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DEDICATION

To my parents.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Using Interactive Visualization to Enhance Understanding of a Fisheries Model

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Fishery management is the science of setting rules for governing fishing so that it is done in a sustainable manner. An ecosystem-based fisheries management (EBFM) approach has been advocated to recognize ecosystems as the complex systems that they are. If EBFM is to be put into effect, fishery managers require ecological models that take many factors into account to help them make management decisions. MS-PROD is o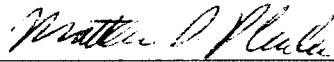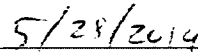ne such model; it is a multi-species production model that forecasts the biomass of ten species of fish in the Gulf of Maine over 30 years. In the model, the biomass of each fish species depends on effects from harvesting and interactions with the other fish species. An interactive visualization of the model was designed and implemented to allow users to investigate the impact of changes in fishing effort in real time. By combining time series with a network representation, this visualization shows the predicted biomasses of the fish, the changes in biomass that can result from changes in fishing effort, the causal relationships that help to explain the effects of changes in fishing effort, and the uncertainty of the model. An evaluation was conducted to compare four different methods for depicting the two types of causal relationships in the model—predation and competition. The evaluation found that representing those relationships with arc diagrams enhanced the understanding of the model. This visualization is a novel combination of time series, a network diagram, user interaction, and a model. The visualization may be a powerful tool that could assist fishery managers in making informed decisions.

CHAPTER 1

Introduction

Fishery managers have only one "lever" to pull when it comes to fishery management: the ability to set harvest quotas. Fishermen work within these quotas by exerting various levels of fishing effort. Production models have been designed to help managers and fishermen understand the ecosystem they work within and the implications of their decisions. In this context, a production model is a mathematical model, based on data, that simulates interactions between species and predicts species biomass as a function of the distribution of fish species population, fishing effort, climate change, and other variables. MS-PROD is a multispecies production model developed by NOAA scientists Gamble and Link (2009). A visualization may enhance such a model by making its inner workings more explicit and may be useful for decision making. The goal of this research has been to explore design alternatives and evaluate the effectiveness of different modes of portrayal and interaction to make a visualization of the MS-PROD model that will be a valuable tool to modelers and stakeholders alike.

1.1 Models

Both the short- and long-term effects of human exploitation on an ocean ecosystem, such as the species inhabiting the Gulf of Maine, are not easily understood. Experiments that would allow ecosystem managers to investigate the impact of different levels of exploitation over many years are either impractical or impossible to conduct on a large scale. Fortunately, ecosystem models can be used instead to help gain a better understanding of an ecosystem.

1.1.1 Lotka-Volterra Equations

Ecosystem models are abstract representations of an ecological system, and can range from an individual species in its environment to an entire community of species. A classic example is the Lotka-Volterra model, which is a pair of differential equations for describing the non-linear interactions between a predator species and a prey species (Lotka; Volterra, 1926; 1926):

$$\frac{dN_1}{dt} = N_1 \left(\alpha - \beta N_2 \right) \tag{1.1}$$

$$\frac{dN_2}{dt} = -N_2 \left(\gamma - \delta N_1 \right) \tag{1.2}$$

where N_1 is the number of prey animals, N_2 is the number of predator animals, t is time, α is the prey animals' growth rate, β is the rate at which the predators destroys the prey animals, γ is the death rate of the predators, and δ is the rate at which the predators increase from consuming the prey animals. The model can be generalized to discuss an arbitrary number of species rather than just a single pair.

The Lotka-Volterra model can be modified to take competition instead of predation into account, as in the Rosenzweig-MacArthur model (Rosenzweig and MacArthur, 1963) and the Leslie-Gower model (Leslie and Gower, 1960). These adaptations also consider carrying capacity, which is the maximum number of a species that can be sustained indefinitely in a particular environment:

$$\frac{dN_1}{dt} = r_1 N_1 \left(1 - \left(\frac{N_1 + \alpha_{12} N_2}{K_1} \right) \right) \tag{1.3}$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(1 - \left(\frac{N_2 + \alpha_{21} N_1}{K_2} \right) \right) \tag{1.4}$$

where r_i is the growth rate for species i, K_i is the carrying capacity for species i, and α_{ij} is the effect species j has on species i. As with Lotka-Volterra, this model concerns only two

species, but it can be generalized to include more than two.

Both Lotka-Volterra and Leslie-Gower do not incorporate a factor that is critical when discussing fisheries management: the effect of harvest. The Schaefer model adds a term to account for the effect of harvest on an individual species (Schaefer, 1957):

$$\frac{dN}{dt} = rN\left(1 - \left(\frac{N}{K}\right)\right) - qEN \tag{1.5}$$

where N is the number (or biomass) of the species, r is the growth rate, K is the carrying capacity, q is the catchability coefficient, and E is the fishing effort.

Simple models, when available and correct, are generally preferred; since fewer components are needed to describe their real-world counterparts, they are more easily understood and implemented. All three of these models are subjectively simple in that they only consider a few ecological factors each. However, in reality, ecosystems are complex systems that require management that recognizes them as such (Christensen et al., 1996). Thus, a more holistic approach called ecosystem-based fishery management (EBFM) has been advocated (Panel, 1999). However, this approach has not often been implemented due to a lack of models that consider all necessary ecological factors. Gamble and Link developed a multispecies production model (MS-PROD) to fill this gap (2009).

1.1.2 The MS-PROD Model

The MS-PROD model forecasts biomass for species separated into functional groups, which are biological groupings of species that perform similar functions within their ecosystem. The model is built upon the Schaefer production model and also includes Lotka-Volterra terms for predation, Leslie-Gower terms for competition, and carrying capacities for functional groups (K_G) as well as for the entire system (K_σ):

3

$$\frac{dN_i}{dt} = \underbrace{r_i}_{\substack{\text{Growth} \\ \text{rate}}} N_i \left(\underbrace{1 - \frac{N_i}{K_G}}_{\substack{\text{Prevents} \\ \text{infinite} \\ \text{growth}}} - \underbrace{\frac{\sum_{j=1}^{g} \beta_{ij} N_j}{K_G} - \frac{\sum_{j=1}^{G} \beta_{ij} N_j}{K_\sigma - K_G}}_{\text{Competition}} \right) - \underbrace{N_i \sum_{j=1}^{P} \alpha_{ij} N_j}_{\text{Predation}} - \underbrace{H_i N_i}_{\text{Harvest}} \qquad (1.6)$$

where N_i is the number (or biomass) of species i, t is a unit of time, r_i is growth rate for species i, β_{ij} is the competition of species j on i, α_{ij} is the predation of species j on i, H_i is the harvest rate on species i, g is the number of species within species i's group, G is the number of groups, and P is the number of predators.

This model is distinguished from other multispecies production models by describing stocks with explicit ecological and harvest factors. Each species to be included in the simulation must be specified in the parameter file by listing growth rate, functional group membership, initial biomass, carrying capacity, and catchability. Additionally, matrices representing inter-species relationships must be provided to describe the relationship between every pair of species. Such matrices are required for *predation*, where one species consumes the other, and *competition*, where one species affects the other in any manner besides predation. (In ecology, the word "interaction" is often used instead of "competition," but we have chosen to use "competition" so that the term "interaction" will not be overloaded since "interaction" has a separate meaning in a visualization context.)

The MS-PROD authors provided us with a parameter file that contains ten key species chosen from the Northeast United States Continental Shelf Large Marine Ecosystem (NEUS LME), listed here by functional group (in bold):

- **Elasmobranchs:** Skates, Spiny Dogfish

- **Flatfish:** Windowpane, Winter Flounder, Yellowfin Tuna

- **Groundfish:** Cod, Haddock, Redfish

- **Small Pelagics:** Herring, Mackerel

4

The MS-PROD model runs simulations for 30 years with an annual time step to predict individual biomasses. While this output information is potentially valuable to fishery managers, it lacks an interactive graphical user interface.

1.2 Visualization Methods

When designing any complex interactive visualization, a large number of design choices must be made. This section reviews existing research of visualization methods that have relevance to the problem of creating an effective interface to a fisheries ecosystem model—in particular, methods for representing time series, networks, causality, and uncertainty.

1.2.1 Time Series

Fisheries management is focused on the sustainability of choices concerning fish stocks. A main purpose of ecosystem management is to ensure that future generations can enjoy the same natural resources (Christensen et al., 1996). As such, the MS-PROD model provides biomass forecasts for 30 years. Therefore, visualization techniques for temporal data must be explored.

Line Charts

The line chart was first invented by William Playfair in 1786 to communicate time series data, seen in Figure 1-1 (Playfair, 1786). Today, it remains a common method for visualizing time-oriented data in many fields, including science, economics, planning, and engineering to name a few. Line charts typically encode time on the horizontal axis, progressing from left to right, and some time-varying value on the vertical axis. Points in the chart are connected by line segments such that the slope of the line indicates the rate of change between time steps.

Multiple time series can be part of a single line chart; each series needs only to be distinguished by a color and/or line style. However, as the number of time series on a single line chart increases, it becomes more difficult to identify an individual series. Javed
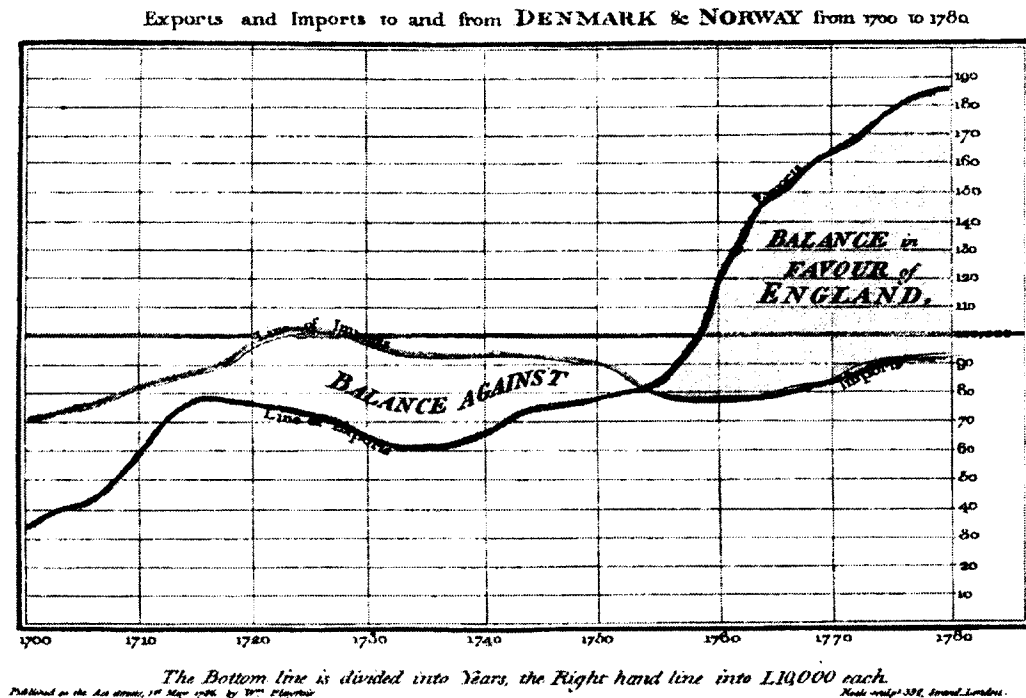
Figure 1-1: Playfair's original time series chart (1786). Public domain.

et al. evaluated the four different plotting techniques for multiple time series illustrated in Figure 1-2 (2010). The first of the techniques is the "simple line chart," which is Playfair's original line chart with all series plotted together. A slight variation on that is "small multiples," where each series has its own line chart though all charts share the same axis scales. Horizon graphs, originally developed by Saito et al., wrap around a baseline in two color tones to save space (2005). Lastly, braided graphs feature all series on one chart with the coloring under the curves alternating as series intersect each other. The user evaluation by Javed et al. revealed that a simple line graph with all time series on one plot or a single graph for each time series is better suited to a variety of tasks than a horizon graph or a braided graph. They also found that users complete tasks more correctly when there is more display space allocated to the graphs. They did not recommend using a higher number of simultaneous time series—their study used eight at the most—because it leads to a decline in correctness of task completion.

(a) A simple line graph.

(b) A braided graph.

(c) Small multiples.

(d) Horizon graphs.
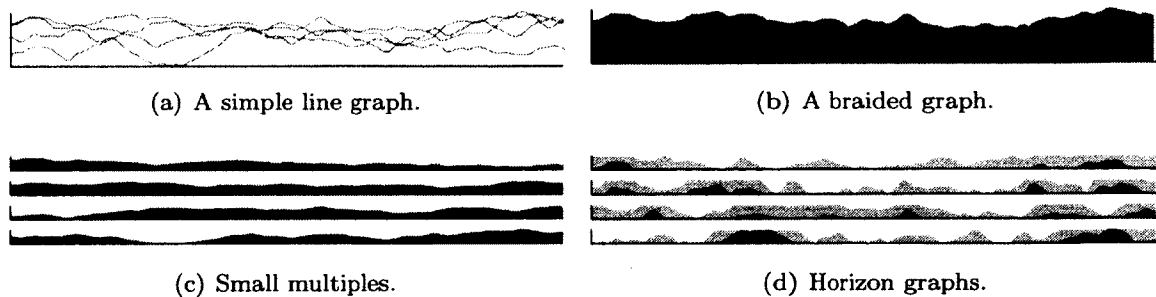
Figure 1-2: Four possible methods for visualizing multiple time series. Reprinted from *IEEE Transactions on Visualization and Computer Graphics*, Vol 16, Javed et al., Graphical perception of multiple time series, 927–934, ©2010, with permission from IEEE.

(a) Shape parameter of 1.0.

(b) Shape parameter of 0.074.
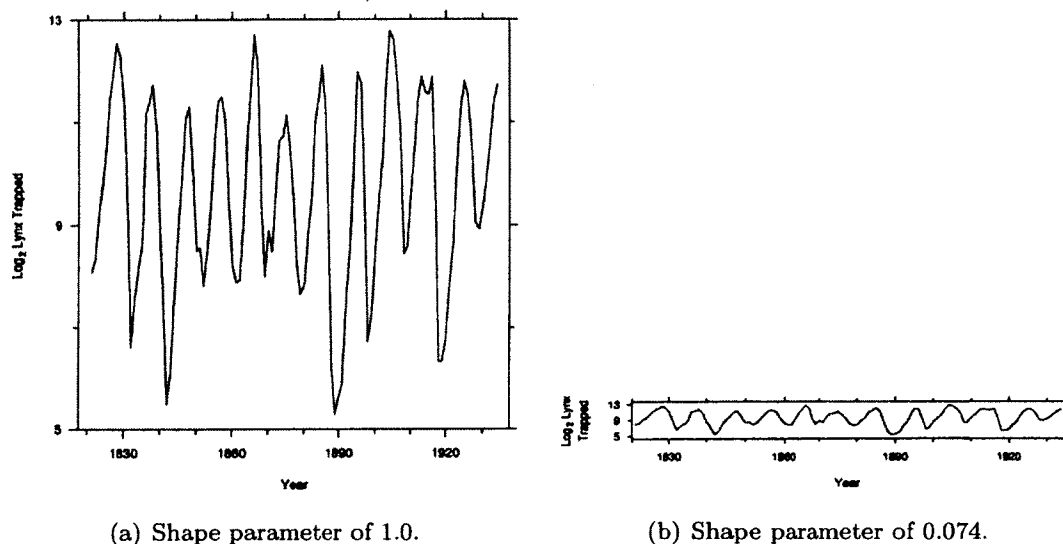
Figure 1-3: Two effects of chart shape on Canadian lynx data. Reprinted from *Journal of the American Statistical Association*, Vol 83, Cleveland et al., The Shape Parameter of a Two-Variable Graph, 289–300, ©1988, with permission from Taylor & Francis.

7
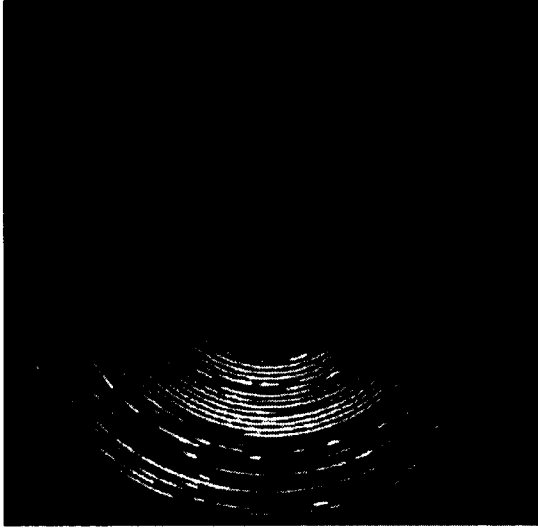
(a) Spiral time series. Reprinted from *IEEE Symposium on Information Visualization*, Weber et al., Visualizing time-series on spirals, 7–13, ©2001, with permission from IEEE.
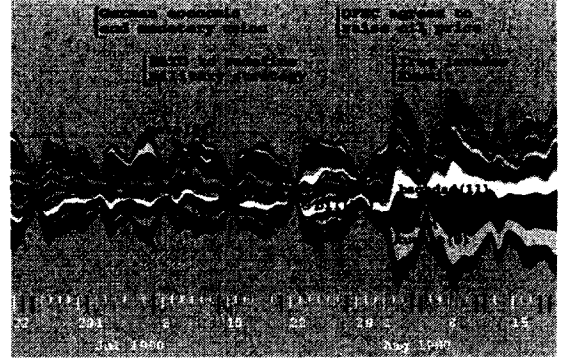
(b) ThemeRiver time series. Reprinted from *IEEE Symposium on Information Visualization*, Havre et al., ThemeRiver: visualizing theme changes over time, 115–123, ©2000, with permission from IEEE.

Figure 1-4: Two alternative time series visualizations.

Some line charts are more effective at conveying the nature of the data than others because of the way different drawing techniques affect interpretability. Cleveland et al. found the shape of a line chart—defined as the height of the chart divided by the width of the chart—to be a critical factor (1988). The shape of the chart directly impacts the slopes of line segments, which viewers interpret in order to understand the dependence of the y variable on the x variable. Figure 1-3(a), a time series of Canadian lynx trapping data, features a shape of 1.0 and seems to imply rapid increases and decreases in the population. Figure 1-3(b) features the same data though with a shape of 0.074, which shows more clearly that the population rises somewhat steadily and declines somewhat rapidly, while Figure 1-3(a) failed to show this. Their user evaluation found that judgment of two slopes is influenced by the orientation mid-angle, defined as the average of the minimum slope orientation and the maximum slope orientation. They proposed line chart shape should be selected such that orientations are as close to ±45° as is possible, like in Figure 1-3(b).

8

Alternatives

There are many alternatives to and variations of Playfair's original time series. One example is Weber et al.'s spiral time series, seen in Figure 1-4(a) (2001). The spiral time series was designed for cyclic data. Cycles are emphasized in a properly-parameterized spiral visualization, however it may be difficult to describe periodic behavior in unknown datasets or determine if that behavior even exists. Another example is the ThemeRiver by Havre et al, seen in Figure 1-4(b) (2000). Each "current" in the ThemeRiver represents an entity or subject and must be of a distinctive color. Positioning along the y-axis is meaningless, instead the abundance of the entity or subject over time is indicated by the width of the band of color. The overall width of the stream is the sum of the widths of all individual bands.

1.2.2   Networks

The input parameters to the MS-PROD model includes predation and competition matrices. The model may be better understood if these relationships can be incorporated into the visualization. Relationships are often visualized through a node-link diagram, which typically represents entities as nodes and links as relationships between the nodes they connect. There are many types of node-link diagrams used for illustrating networks; those which are relevant to our research are discussed in the following sections.

Force-Directed Layouts

One option for showing fish species interactions would be to use a force-directed layout as Gaichas and Francis did, seen in Figure 1-5 (2008). Here, the nodes represent an individual species in the Gulf of Alaska, while the links represent a predator-prey interaction. In a force-directed layout, nodes repel each other, while related nodes become pulled toward each other by links (Heer et al., 2010). The result is an aesthetically pleasing layout where there are relatively few link crossings and links are of approximately similar length. The color of the node can be used to indicate group membership, while the size can represent
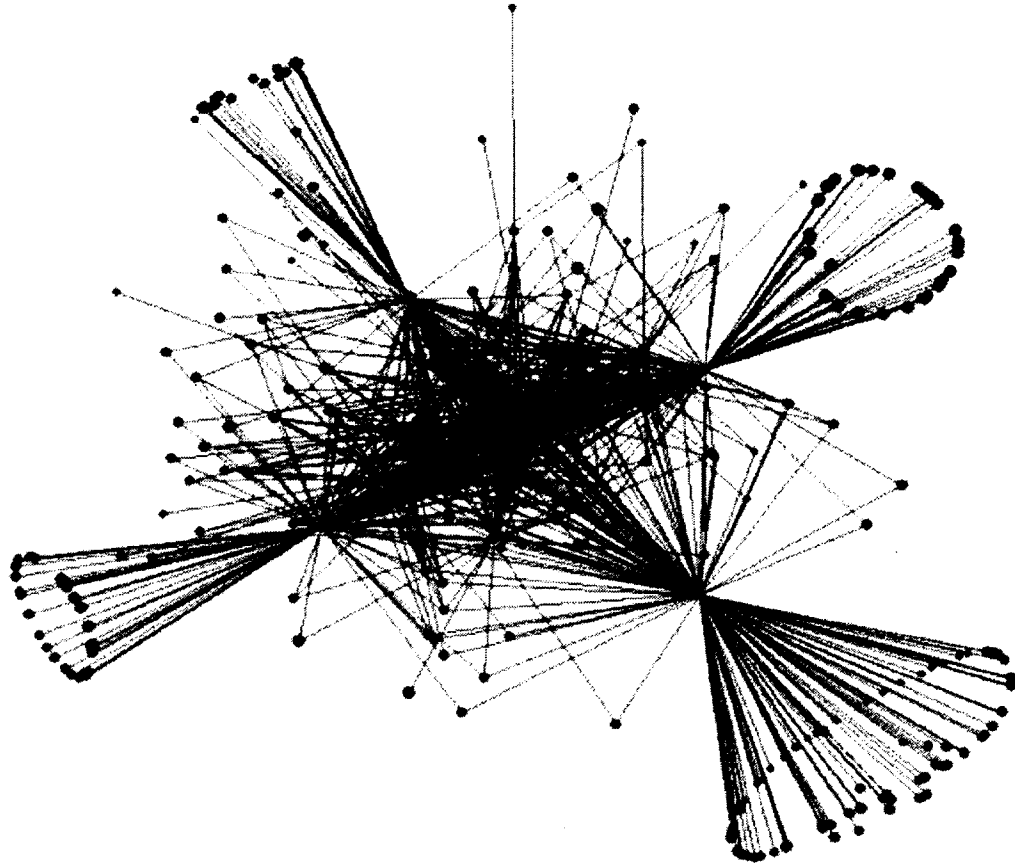
Figure 1-5: A force-directed visualization of a food web of Gulf of Alaska data. Reprinted from *Canadian Journal of Fisheries and Aquatic Sciences*, Vol 65, Gaichas and Francis, Network models for ecosystem-based fishery analysis: a review of concepts and application to the Gulf of Alaska marine food web, 129–130, ©2008, with permission from Elsevier.

the magnitude of some property of the node. Likewise, the drawing style of the link can be varied to encode different types of relationships. Depending on the size of the network, a force-directed layout can be dense, as shown in Figure 1-5, making it difficult to discern individual nodes or links. Interactive methods can alleviate this by allowing the user to zoom or to click a node and see only the subset of the network directly connected to that node.

Arc Diagrams

An alternative for force-directed layout is an arc diagram. The name arc diagram was coined by Wattenberg (2002), though they were invented earlier. Knuth used arc diagrams to
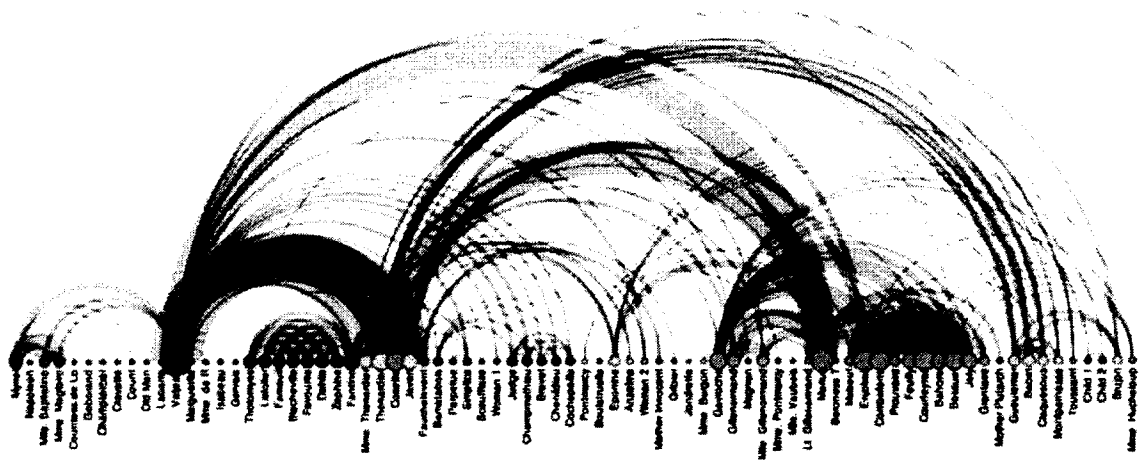
Figure 1-6: Knuth's arc diagram of *Les Misérables* characters. Image reproduced with permission from Jeffrey Heer.

illustrate interaction of characters in Victor Hugo's novel *Les Misérables*, seen in Figure 1-6 (1993). Each character is represented with a circular node, where size indicates the number of appearances in the novel. The nodes are arranged linearly, colored and ordered according to clusters of characters that appear together frequently. Semi-transparent arcs are drawn between the characters who appear in the same chapter, with the thickness of the arc representing the number of such appearances. While the arc diagram may fail to properly depict the structure of a network, Heer et al. point out it is advantageous because the one-dimensionality allows for other features to be easily displayed near the nodes (2010), such as text labels.

Directed Edges

Relationships in a network may be directional, such as the predator-prey relationship. In a visualization of such a network, the direction of the edges must be encoded so these relationships can be understood. Holten and van Wijk studied the effectiveness of different techniques for indicating directionality of edges in a graph, seen in Figure 1-7 (2009). The traditional arrowhead was found to perform poorly, while tapered edges performed best. As
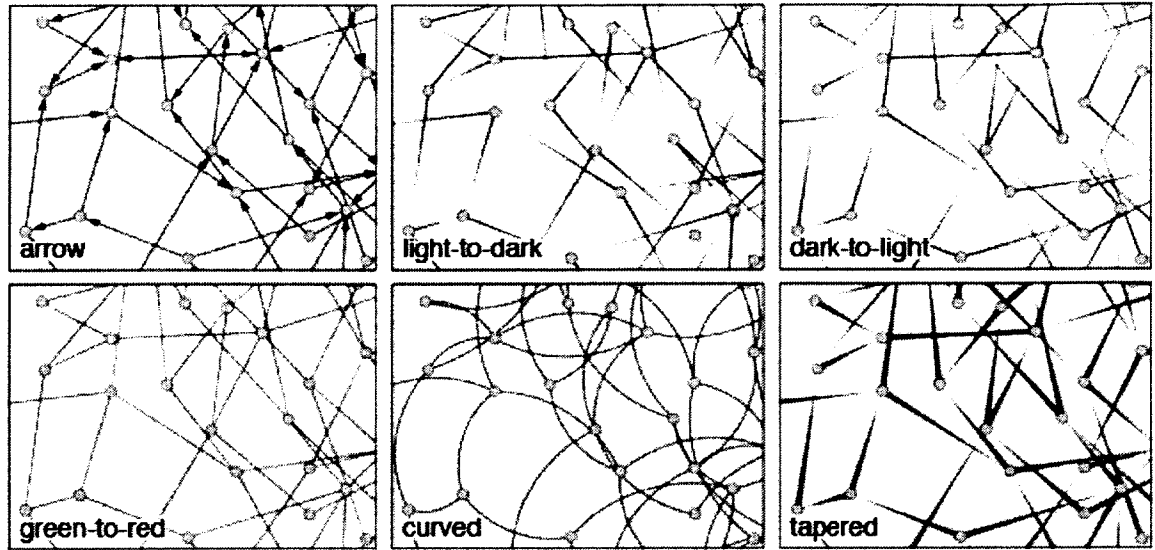
Figure 1-7: Different types of directed edges.

for an intensity-based direction cue, a dark-to-light representation was found to be clearer than light-to-dark.

Matrix Representations

Node-link diagrams can have occlusion problems when they are highly-connected, so a matrix-based representation of a network is a possible alternative (Heer et al., 2010). In many cases, networks are stored as an adjacency matrix, so all that needs to be done is visualize that matrix as a grid, where the cell at the ith row and the jth column represents the relationship from entity i to entity j. Figure 1-8 shows Knuth's visualization of *Les Misérables* characters in matrix-form (Knuth, 1993). The color of the cell indicates the presence or type of a relationship, with some neutral color indicating the lack of a relationship. Ghoniem et al. showed that a matrix-based view is suitable for large or dense networks for tasks that involve finding or counting links or nodes (2004). With proper ordering of the rows and columns, the structure of the network can be effectively displayed, however path-finding tasks may be difficult.

Figure 1-8: A matrix-based visualization of an adjacency matrix. Image reproduced with permission from Jeffrey Heer.

1.2.3 Causality

Gamble and Link found that both inter-species relationships and harvesting by humans can contribute to changes in species biomass according to their MS-PROD model (Gamble and Link, 2009). For example, an increase in biomass for one species could possibly hinder growth for another species. Because this is a type of cause and effect relationship, it is necessary to consider the various techniques for representing causality in a network, especially in an interactive context.

(a) Pinball.   (b) Prod.   (c) Wave.
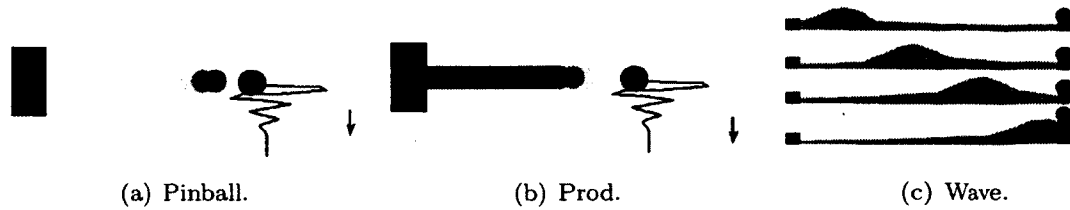
Figure 1-9: Three metaphors for conveying causality. Reprinted from *IEEE Symposium on Information Visualization: Late Breaking Hot Topics*, Ware et al., Visualizing causal relations, 39–42, ©1999, with permission from IEEE.

Michotte and Thinés suggested that viewers infer causality when viewing an object being set into motion after being struck by another object (1963). This served as a basis for Ware et al.'s visual causality vector (VCV), which communicates causal relationships between two nodes in a network visualization (1999). They studied how several animated metaphors—shown in Figure 1-9—and different timing rules for a VCV affect the perception of causality. Their evaluation showed that temporal synchrony between the animation of the metaphor and the changes in the recipient node is more critical than the type of metaphor for showing causal relationships. Ware later revisited this work in the context of multi-touch screens to convey causal effect enhancements, causal effect reductions, and causal blocking effects using colored pulses (2013). The user evaluation conducted by Ware showed that causal blocking effects and positive enhancements were well understood with this design, while negative causal effects were less reliably judged. Still, these methods were recommended for showing simple causal relationships.

Kadaba et al. expanded upon Ware et al.'s VCV work to compare between static and animated causal visualizations (2007). In their static design, positive influences were indicated with a plus sign (+) glyph and negative influences were indicated with a minus sign (−) glyph attached to the link between two entities in the network, as in Figure 1-10(a). The size of the glyph represented the magnitude of the influence on the recipient node and glyphs of the same color described a multiplication effect on the recipient. Their animated design featured bullets traveling along the links toward the recipient node to indicate causal influences, shown in Figure 1-10(b). As a bullet hit the recipient node, the size of the

Positive effect of
"Flu" represented
by bars along
positive y-axis

Positive Influence of
"Cold Weather" on "Flu"
represented by + sign

Sweets

Low
Immunity

Cold
Weather

Flu
Season

Stress

Flu

Virus

Rest

Medication

Headache

Pnuemonia

Negative Influence of
"Medication" on "Flu"
represented by – sign.

Sweets

Low
Immunity

Cold
Weather

Flu
Season

Stress

Virus

Flu

Rest

Medication

Pnuemo

Small Influence of "Cold
Weather" on "Flu" depicted by
small bullet from "Cold
Weather" to "Flu"

Medium Influence of "Virus" on
"Flu" represented by an
animated movement of bullet
from "Virus" to "Flu"

Large positive effect on "Flu"
by "Cold Weather" and "Virus"
represented by an animated
increase in node size

Sweets

Low
Immunity

Cold
Weather

Flu
Season

Stress

Virus

Flu

Rest

Medication

Headache

Pnuemonia

(a) Static.

(b) Animated.

Figure 1-10: Two alternatives for visualizing causal influences. Reprinted from *IEEE Transactions on Visualization and Computer Graphics*, Vol. 13, Kadaba et al., Visualizing Causal Semantics using Animations, 1254–1261, ©2007, with permission from IEEE.

recipient node changed. They found that subjects can interpret animated and static representations equally accurately, but subjects formed responses slightly quicker with animated representations.

1.2.4 Uncertainty

Because a model is a simplification of reality, there are many reasons why it may be inaccurate. There may be inaccurately estimated parameters used in the model, such as the predation matrix coefficients or the starting values for the biomasses of the fish species. Furthermore, relevant factors may not have been taken into account when designing the model, such as climate. Inaccuracies may even result from approximation techniques, such as the use of a Runge-Kutta method. Therefore, it is common for a model's output to be regarded with some uncertainty. To clarify, *error* describes inaccuracies when the correct answer is known, while *uncertainty* describes inaccuracies when the answer is unknown (Hunter and Goodchild, 1993). Due to uncertainty, model output is best understood as a

15

(a) Error cone.   (b) Cox et al.'s method.

Figure 1-11: Two visualizations of uncertainty for a hurricane advisory. Reprinted from *International Journal for Uncertainty Quantification*, Vol. 3, Cox et al., Visualizing Uncertainty in Predicted Hurricane Tracks, 143–156, ©2013, with permission from Begell House, Inc.

range of expected values that is likely to contain the true value. According to Potter et al., scientific data should be considered to be incomplete without representations of uncertainty (Potter et al., 2010), so we have investigated some different portrayals of uncertainty.

Cox et al. explored methods for depicting uncertainty for hurricane advisories (2013). The traditional error cone, shown in Figure 1-11(a), is used by NOAA's National Hurricane Center, but it can be poorly understood by the average citizen. Cox et al. designed their own alternative representation, shown in Figure 1-11(b), where many possible hurricane tracks are drawn to describe the range of possible outcomes. Their user evaluation found that neither method was significantly better than the other for all cases, but a qualitative analysis showed that nearly all users prefer their new method over the error cone.

1.3   Understanding Models

Users studying models can benefit from the aid of a visualization, because patterns and trends may be difficult—if not impossible—to discern from only a table of numerical values. The learning process can be even further enhanced through interaction with the model. If interactivity is supported by the visualization, users can adjust parameter values, perceive a change (or perhaps no change) in the results, and begin to understand the degree of

(a) A screenshot of VisiCalc. GNU General Public License.
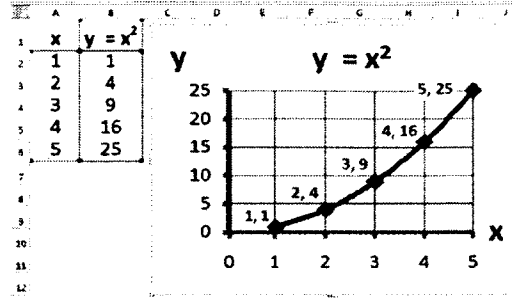
(b) A chart made using Microsoft Excel. Public domain.

Figure 1-12: Two examples of spreadsheet applications.

influence different parameters possess.

1.3.1 Spreadsheet Programs

VisiCalc was a very early example of software assisting the understanding of models through visualizations (Grad, 2007). As a business student, Bricklin wished there was a faster way to change the input or fix mistakes when working out financial models by hand (1999). To address this, he worked with Frankston to develop VisiCalc, seen in Figure 1-12(a). As the world's first electronic spreadsheet, VisiCalc consisted of rows and columns containing either text, numerical values, or formulas. Result cells were instantly updated according to changed inputs or adjusted formulas, allowing a user to work with models in a more efficient and dynamic manner. VisiCalc was superseded by Lotus 1-2-3, which was in turn supplanted by Microsoft Excel. Microsoft Excel remains popular and features graphing tools that can generate charts, such as in Figure 1-12(b).

1.3.2 The Influence Explorer

The Influence Explorer by Tweedie et al. is a good example of a more complex interactive visualization (1995). They developed an interface for understanding the relationships between different attributes in a design process. Design parameter values of the Influence Explorer are initially randomly selected in a Monte Carlo simulation to represent many different possible designs. Each cell in the histogram is a simulation run. For each attribute,

17
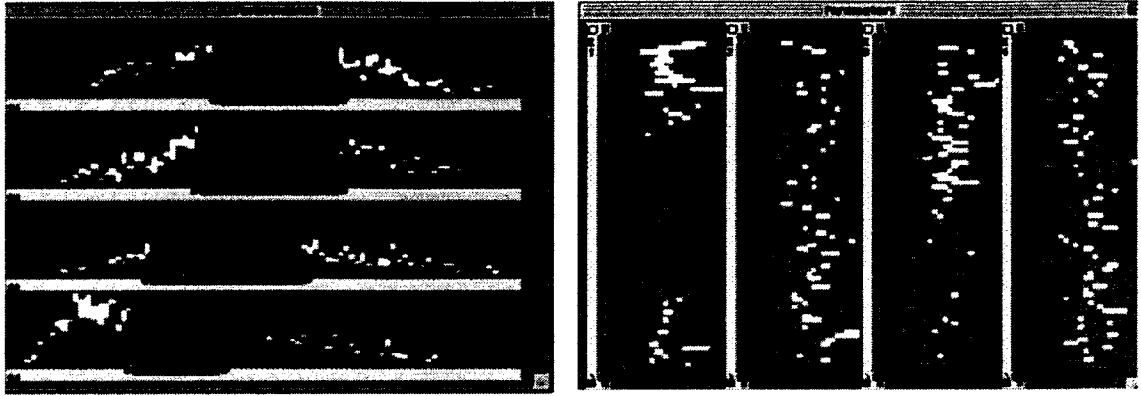
Figure 1-13: A screenshot of the Influence Explorer. Image courtesy of Robert Spence.

there is a histogram including each of the items. The attribute ranges are controlled by sliders. When the user adjusts the slider of a given attribute, all items that are within that range are highlighted on all of the histograms. Figure 1-13 is a screenshot of the Influence Explorer being used to test the performance of different light bulb designs; red indicates the design passed, while the black-to-white scale indicates the number of tests the design failed. In a user evaluation, industrial designers found the ability to interactively explore the effects of different parameter ranges to be valuable.

1.3.3 Vensim

Eberlein and Peterson recognized that both unskilled and skilled model users have the same need: to quickly obtain a thorough understanding of a model and its implications (1992). This motivated their development of Vensim, which is a commercial tool for visualizing and analyzing simulation results. Vensim allows users to run a model under different conditions with a simple mouse click, enabling the user to learn the effects of different actions with ease. Various features enhance this learning process—e.g., "causal tracing" strip graphs, shown in Figure 1-14. Rather than simply seeing a chart of the projected population, a user exploring the causal tracing feature can begin to understand the various components that contributed to the population simulations—births and deaths—by seeing each component on its own chart. A major emphasis of Eberlein and Peterson is that the same visualization
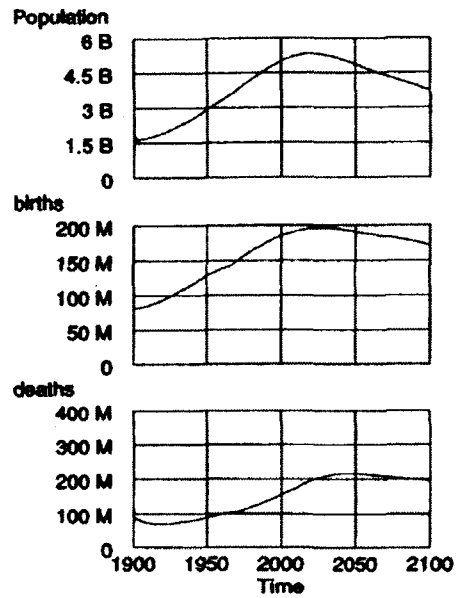
Figure 1-14: A screenshot of the strip graphs in Vensim. Reprinted from *European Journal of Operational Research*, Vol 59, Eberlein and Peterson, Understanding models with Vensim^{TM}, 216–219, ©1992, with permission from Elsevier.

tool can and should be used for both the development and teaching phases of a model, especially since those phases may not be discrete.

CHAPTER 2

Requirements and Design

The motivation of this research is to provide an interactive visualization to the NOAA MS-PROD model that could help fishermen, fisheries managers, and other stakeholders understand the implications of management decisions. In other words, we would like to help them understand the effects of changing catch quotas for particular kinds of fishing activity—e.g., bottom trawling versus mid-water trawling. We planned our interactive interface with the intent that users would gain insight into:

- **Implications of the model:** E.g., how do two different sets of fishing effort values affect the biomass predictions of the ten species?

- **The model itself:** E.g., why does the abundance of one species increase when another species is caught?

To accomplish this goal, we determined that our interactive interface of the MS-PROD model would need to visualize:

- the predicted biomass over time for all modeled species;

- changes in predicted biomass as a result of changes in fishing effort for a subset of species;

- causal relationships which help to explain why the model predicts the effects of changes in fishing effort for a subset of species; and

- uncertainty of the model

Since setting fishing quotas is the only action fishery managers can take, we determined that the only interaction available to users would be to adjust the fishing effort level; all other model parameters are not modifiable once the model and its visualization are running. This interaction is done by means of a set of sliders with the goal of allowing the user to immediately see the impact of management decisions on fisheries. The user adjusts sliders which represent harvest effort and watches the biomass plots change instantaneously as the model is re-run according to the new effort values. The sliders are set to one (1) by default and use a non-linear scale with higher resolution for values less than one, seen in Figure 2-1; this allows the user to see the effects of reducing harvest effort by 25% percent or tripling harvest effort. Like Eberlein and Peterson, we aimed to turn the "time consuming and tedious" task of working with a model into a "fast and fun" interactive experience (1992). Different views and features of the model visualization are described and discussed in the sections below.

Figure 2-1: An example of a slider used to change harvest effort for the MS-PROD model.

It is important to note that the MS-PROD model allows for different fishing effort values for each species for each year in the thirty-year period for which the model produces forecasts. This is to reflect that fishing quotas can change from year to year. Since there are ten species and thirty years, this means there are potentially 300 separate fishing effort values that could be set by a user. However, it would be cluttered and confusing to have an effort slider for each of those 300 values. Therefore, two simplifications were made. First, fishing effort should be controlled by functional group rather than individual; the model authors requested this because it is more realistic than fishing by individual species. Second, fishing effort for a functional group is constant across all thirty years; while this is unrealistic, it is easier to understand and perhaps, in a sustainable, "perfect world," fishing

quotas would not need adjusting over the years. Thus, each slider controls the fishing effort for all thirty years for a particular functional group.

2.1 Visualization of Predicted Biomass

Our first challenge was to decide how to display the thirty-year biomass forecast data output by the model. Time series line charts—of both the simple line chart and small multiples varieties—were chosen because casual viewers can understand them without further instructions, as opposed to, say a horizon graph. Another advantage to line charts is that they tend to have a reasonable amount of whitespace where additional information can be displayed, such as uncertainty or alternate forecasts. A key design issue concerned the representation of change between two forecasts; line charts provide the ability to display this change. A number of alternatives for change were implemented and are described in the sections that follow.

2.1.1 Alternative Screen Layouts

An early design decision concerned the issue of how many individual charts should be used to display the data and how to arrange those charts. Two alternative screen layouts were developed for displaying these time series on line charts: a "four panel" view in Figure 2-2 and a "small multiple" view in Figure 2-3, described in further detail below. With both views, the time series for the species are organized by functional group. A functional group is a biological grouping of species which perform similar functions within their ecosystem—e.g., mackerel and herring are both members of the "small pelagic" group since they live in the water column.

There were a number of reasons behind the decision to arrange by functional group rather than placing all time series on a single line chart. First, harvest effort is controlled by functional group using the sliders, so it must be somehow indicated which species are part of which functional group. With multiple time series, this can be encoded through positioning by arranging the slider of a functional group to be near the time series of that
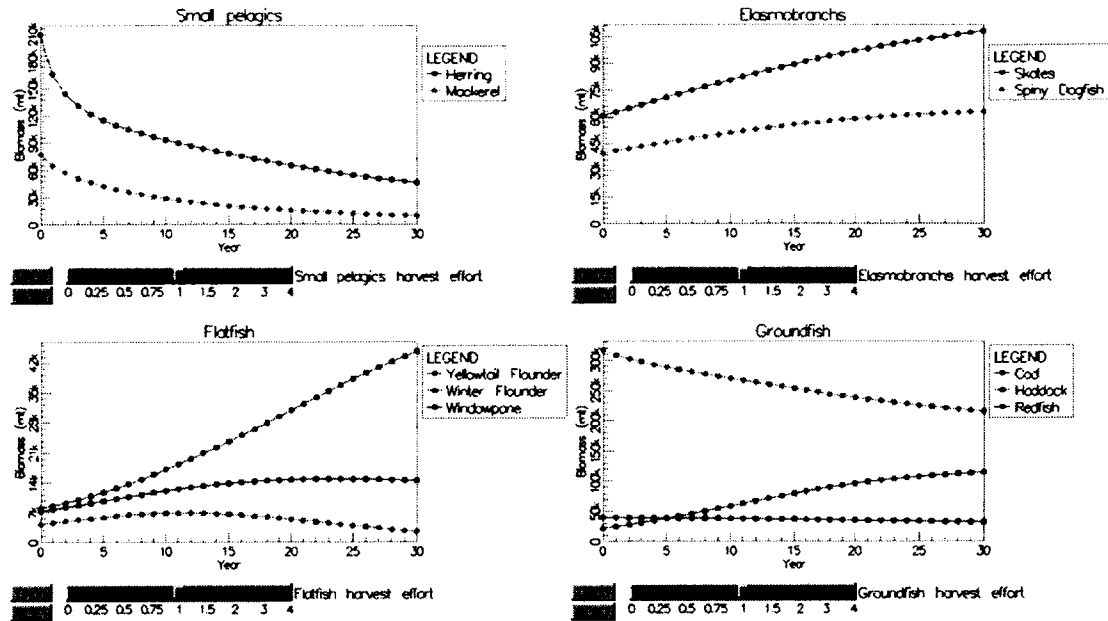
Figure 2-2: The "four panel" view of our MS-PROD visualization.

group's species. Second, the biomass of some species is significantly larger than others. By scaling the y-axis according to the largest biomass value of all species in the entire 30-year time span, the lines representing some species would have been crowded at the bottom of the chart and seemed to be flat even when they were not.

Four Panel View

We observed that species of similar functional groups tend to have biomass values in similar numeric ranges, so we decided to have one line chart per functional group for displaying biomasses. This view is called the "four panel" view and is shown in Figure 2-2.

The major advantage of this "four panel" view is that comparison of species within a group is easy. For MS-PROD, there are only two or three species per functional group, so the line chart for each group seldom suffers from occlusion problems. Direct and indirect effects of changes in harvest effort are easily differentiated with the "four panel" approach—e.g., if the user adjusts the effort slider only for elasmobranchs, yet sees the biomasses change on the groundfish chart, the user can begin to understand there is some kind of relationship between elasmobranchs and groundfish.
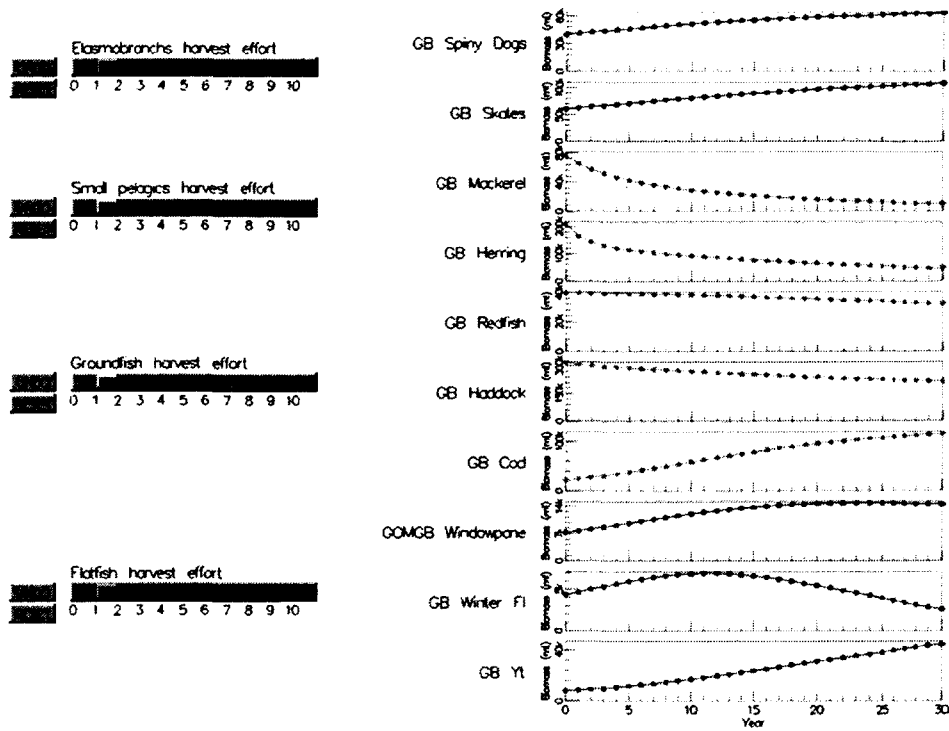
Figure 2-3: The "small multiples" view of our MS-PROD visualization.

Small Multiples View

The alternative to the "four panel" view is to see each species on its own plot, which we call the "small multiple" view. The main purpose of this view is to support the addition of arc graph connections between species, as discussed in Section 2.3.1. Shown in **Figure 2-3**, each plot is sorted and colored according to functional group membership. The harvest effort sliders are also colored by functional group and positioned near the plots of the corresponding group. This allows for the ability to differentiate between direct and indirect effects of changes in harvest effort.

With each species on its own plot, it is much easier to interpret the biomass predictions of an individual species, since the y-dimension of a plot can be scaled to the data of one species only. It is also easier to perceive increases or decreases in biomass because no species suffer from the "flattening" that can occur when a series is displayed on the same plot as a series that has significantly higher values. On the other hand, this makes biomass comparison between species somewhat difficult because all the y-axis scales are different

24
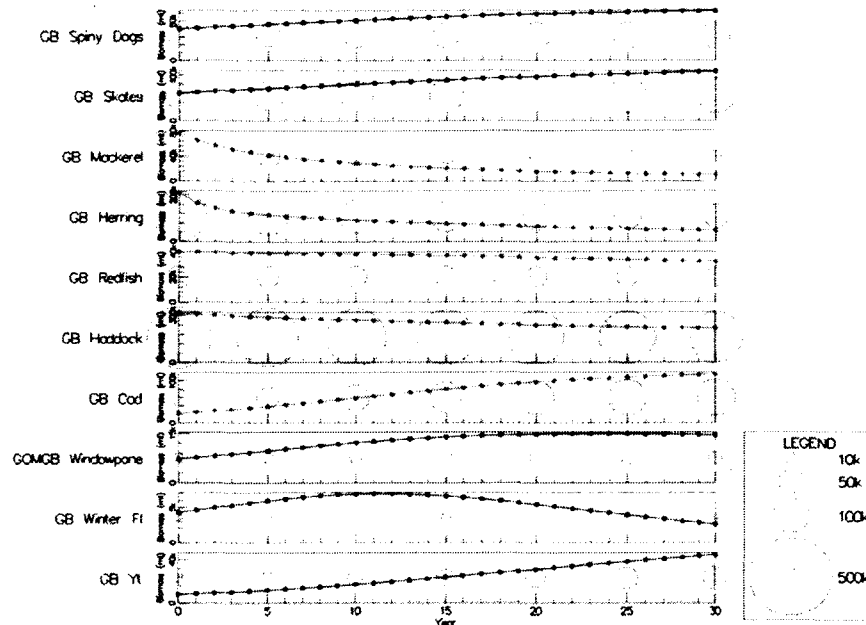
Figure 2-4: Absolute biomass indicators overlaying the "small multiples" view.

and the user must either refer to the y-axis labels or hover over a specific point on a chart, which causes a label to appear, in order to determine the absolute value of the biomass at a point in time.

Absolute Biomass Indicators

Absolute biomass indicators, seen in Figure 2-4, were introduced to depict how biomass changes over time by showing the absolute biomass of the population as the area of a circle. This makes comparison across species possible. To avoid occlusion, these indicators are drawn every five years within the thirty-year time span.

2.2 Visualization of Change

In order for modelers and other stakeholders to understand and compare decisions, users must be able to perceive changes in biomass resulting from changes in the fishing effort. Therefore, we introduced a feature that allows the user to compare the forecast effects of a change in fishing effort to the forecasts of the *status quo* (the baseline). There are three
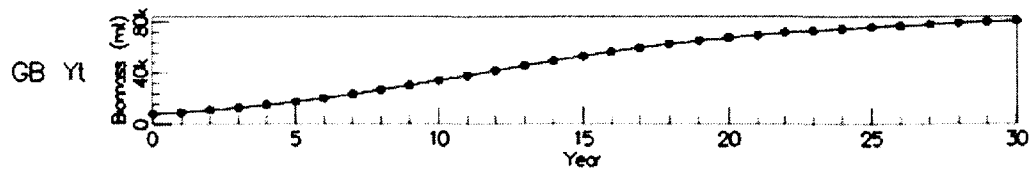
(a) Change shown by interaction.
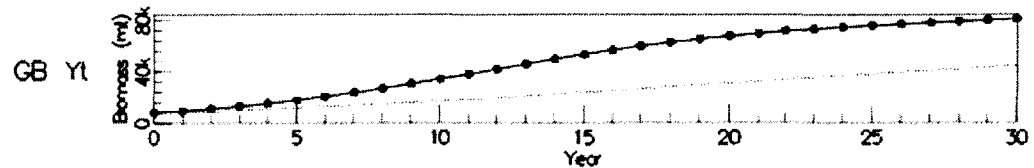
(b) The status quo is shown as the dotted gray line.
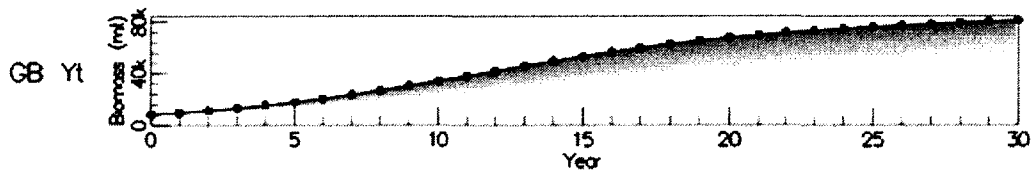
(c) The area between the status quo graph and the new forecast is shaded.

Figure 2-5: The three options for depicting change between current biomass predictions and baseline predictions.

alternatives for displaying forecast differences with the baseline. The first is to simply have the biomass plots change instantaneously as the harvest effort sliders are adjusted, as in Figure 2-5(a). In this case, the user must remember the previous curve in order to judge a change. The second is a dotted gray line which shows the forecast of the baseline in addition to the current forecast, shown in Figure 2-5(b). The third is a shaded area originating from the curve of the current forecast that diminishes in opacity as it approaches the curve of the baseline forecast, as in Figure 2-5(c).

Figure 2-6 shows all of the time series in the "small multiples" view with the effort sliders and the blended change option enabled. Again, the blended area in a line chart is colored from the current biomass line to the line as it was when the baseline was set; a colored area above the line indicates the biomass declined, while a colored area beneath represents the biomass increased—e.g., the "skate" population declined dramatically with the new effort values, the "winter flounder" population increased due to the changes, and "redfish" seemed to be unaffected.
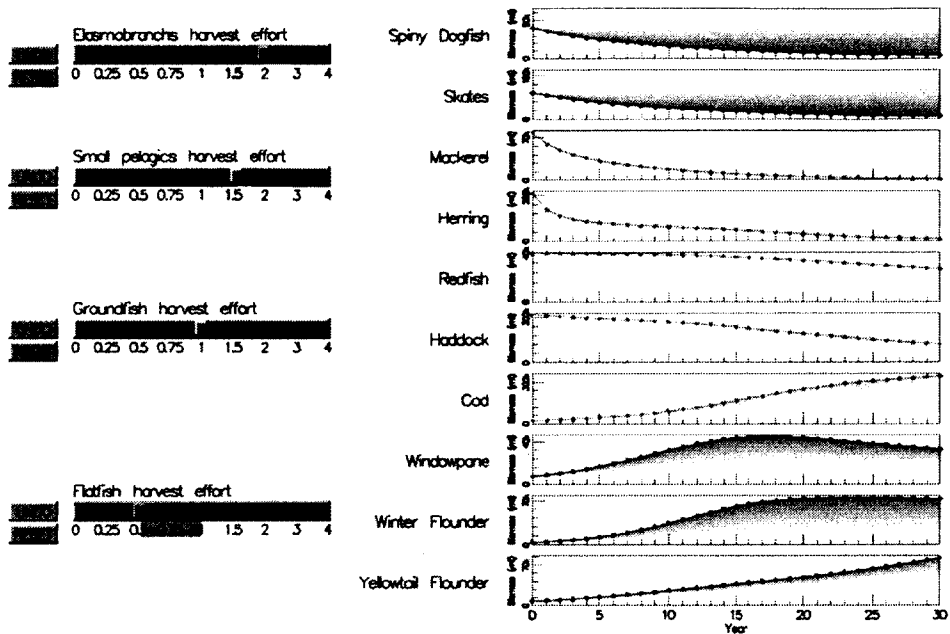
Figure 2-6: Showing change between different effort values.

Underneath each slider, a colored rectangle—if present—indicates differences from the baseline effort settings. Blue indicates the effort value has been increased since the baseline was set—e.g., again in Figure 2-6, the effort for "elasmobranchs" was originally set to 1.0 and now it is approximately 2.0. Red represents the effort value has been decreased since the baseline was set—e.g., the effort for "flatfish" was originally set to 1.0 and now it is approximately 0.5.

This feature is available in both the "four panel" and "small multiples" views. The baseline effort setting can be defined at any time with a simple button at the top of the screen. This resets the baseline as the current slider settings. Buttons are also available to undo or reset changes to the effort values.

2.3   Visualization of Causal Relationships

Understanding the model requires an understanding of the underlying relationships between species—namely, *predation* and *competition*—and *harvest*. As defined earlier, predation is when one species consumes another and competition accounts for any way one species might

27

affect another in a way that is not predation. Harvest is the process of humans catching fish in the wild. Our interface must explain to users which species impact each other, how harvesting impacts the species, and the magnitude of those relationships. We have chosen to illustrate these relationships with a node-link diagram, where the nodes are the time series and effort sliders.

2.3.1   Inter-Species Relationships

The inter-species relationships are illustrated with arc diagram network visualizations between time series, as in Figure 2-7, in the small multiple view. In the input parameter file, predation and competition coefficient matrices are defined to represent the relationship between each pair of species. Each non-zero coefficient is represented with an arc connecting the time series plots of the corresponding species. This is only available in the small multiples view because multiple species are represented in each line chart of the four panel view.

The arc diagrams are easily combined with the small multiples; in fact, small multiples were chosen because they would work with an arc diagram. A separate node-link diagram, such as one with a force-directed layout, may have been confusing because it would require the user to mentally associate the randomly distributed nodes in the network with line charts. An arc diagram does not suffer from this problem since, in our case, the time series themselves are the nodes. Furthermore, the arc diagram enhances the entire visualization without occluding the time series. Arc diagrams are also well suited to smaller datasets with clusters of nodes, which applies to our dataset since the fish are segmented into functional groups.

Directionality

The predation and competition relationships are directed, where one species of fish is the "source" and the other species is the "recipient." Therefore, our arcs have been drawn with fading opacity to indicate the direction, since Holten and van Wijk recommended a dark-to-
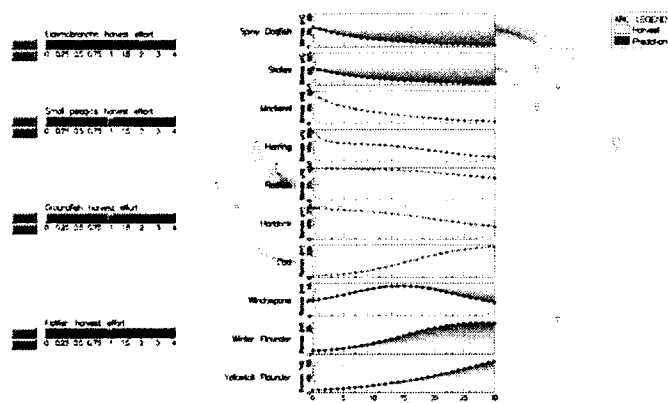
(a) Predation arcs.
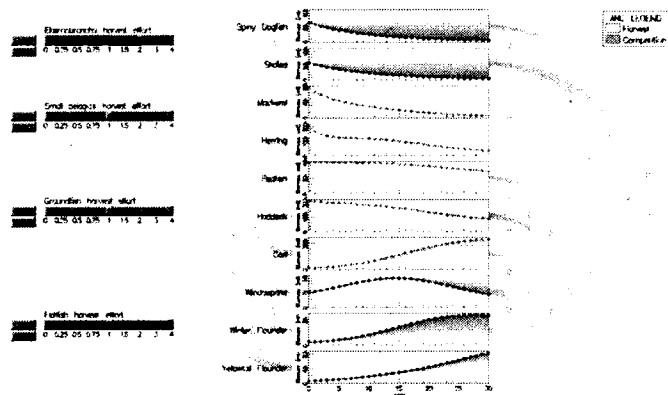
(b) Competition arcs.
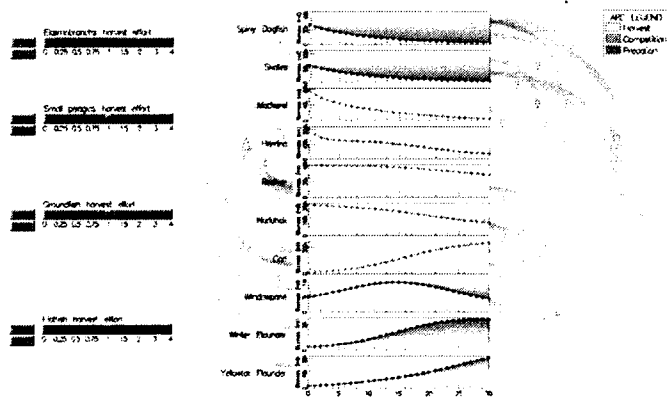
(c) Both types of arcs.

Figure 2-7: Static arcs drawn between species charts to represent relationships.
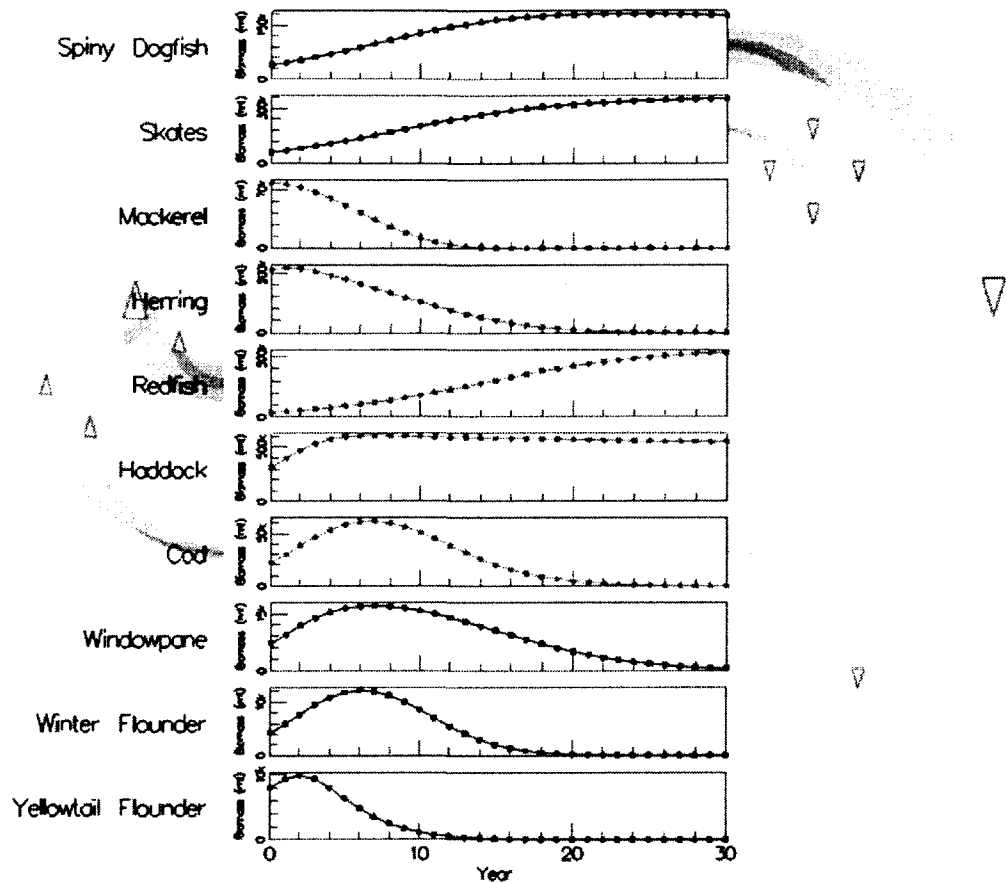
Figure 2-8: Static predation arcs with directionality indicated by a triangular arrow, fading color intensity, and clockwise direction.

light representation for an intensity-based cue (Holten and van Wijk, 2009). Additionally, our arcs follow a clockwise direction; arcs on the right-hand side are all directed downward, whereas arcs on the left-hand side are directed upward. The arcs can also be animated with a pulsing effect that originates from the source species to the recipient species. These directional cues are necessary because there may be reciprocal "Fish A affects Fish B" and "Fish B affects Fish A" relationships, especially for the competition type of relationship, so arcs must be drawn on both sides of the time series, as seen in Figure 2-7. Additionally, triangular marks have been drawn in the middle of the arcs to point from the source species to the recipient species. These three directionality cues can be seen in Figure 2-8.

Arc Type

The interface provides a few options for viewing the inter-species relationships. First, users have the ability to view either predation as in Figure 2-7(a), competition as in Figure 2-7(b), or both as in Figure 2-7(c). Second, the arcs can be viewed statically, dynamically without animation, or dynamically with animation; these three arc types are described below. Regardless of the selected arc type, all predation arcs are colored orange and all competition arcs are colored sky-blue. The user can mouse over a particular arc, which causes that arc to highlight—while the other arcs fade—and displays a label that spells out the relationship in words and shows the input parameter matrix original coefficient—e.g., "Skates compete with Winter Flounder (0.6)."

Static With the static style of the arcs, all arcs are drawn at all times, as shown in all three sub-figures of Figure 2-7. The width of an arc corresponds to the magnitude of the relationship, as defined in the predation coefficient matrix or the competition coefficient matrix in the original parameter file. A benefit of this type of arc is that it is possible to see all interactions between the species at all times. However, the downside is that viewing all arcs at once can be overwhelming because the display becomes somewhat cluttered.

Dynamic Dynamic arcs, shown in Figure 2-9, were motivated by need to (1) clarify the size change in a causal influence path and (2) eliminate or at least reduce the visual clutter created by the static arcs. We considered the fact that many users might use our interface as a means of comparing two biomass forecasts that resulted from changes in fishing effort values. Such users might wonder what specifically caused the differences between the two forecasts, especially if there are indirect, unintuitive effects. Therefore, we designed dynamic arcs, which are drawn only selectively to help explain the differences between the current forecast and the baseline forecast.

The dynamic arcs are a simplification of a time series of effects, where the width of each arc is proportional to both the original predation or competition coefficient and a weight w:

$$w = \frac{100000}{r_0 + 100000} \cdot (s_{30} - s'_{30}) \qquad\qquad (2.1)$$

where r_0 represents the initial biomass of the recipient species, s_{30} is the biomass at year 30 for the source species according to the current forecast, and s'_{30} is the biomass at year 30 for the source species according to the baseline forecast. If the source species biomass at year 30 did not change between the forecasts, then $(s_{30} - s'_{30})$ equals zero, resulting in a w of zero, so the arc will not be drawn. In other words, the source species must have experienced change between the two forecasts in order to possibly explain a change that occurred in the recipient species; if there was no such change, then no arc is drawn. The width of the arc increases as the difference between the two forecasts for the source at year 30 increases. The arc width is inversely proportional to the size of the recipient species because relatively small species will have a low impact on large species. The constant 100,000 was chosen because it is an approximate biomass average across all species.

To summarize, the width of an arc in dynamic mode is

1. *proportional* to the difference for the final values of the baseline and current forecasts for the source species and

2. *inversely proportional* to the initial biomass of the recipient species.

Therefore, no arcs are drawn when the current forecast and the baseline forecast are the same. As the sliders are adjusted either positively or negatively, more arcs may appear to assist in explaining indirect effects. An arc grows in width as the source species experiences more dramatic change between the forecasts.

Additionally, the weight w is negative if $s_{30} < s'_{30}$. This is significant in explaining *how* the change in the source species affects the recipient species—i.e., was the change that the source species experienced "good" or "bad" from the perspective of the recipient species? Both relationships, competition and predation, inhibit the growth of the recipient species because the source species either consumes the recipient species itself or its resources.
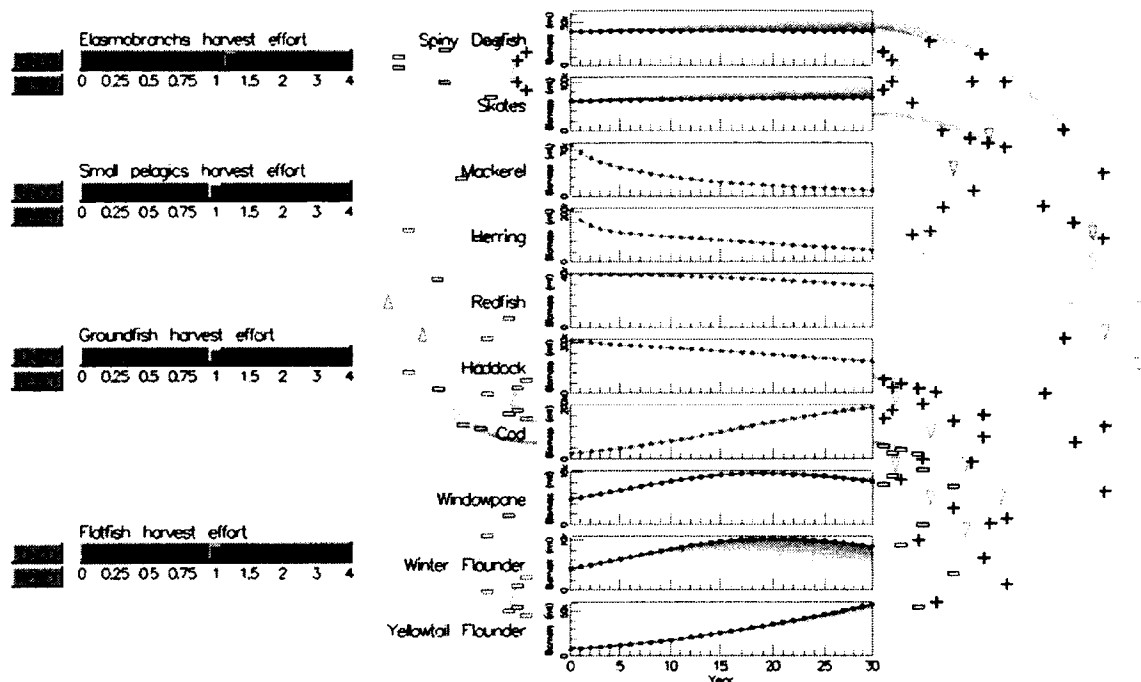
Figure 2-9: Dynamic arcs drawn as a result of slightly increasing the fishing effort on elasmobranchs.

Therefore, if the source species biomass decreases, then the recipient species biomass may be able to grow more. Of course, other species may be dampening the growth of the recipient species, so the recipient species may not necessarily experience a growth, but the potential exists. Conversely, if the source species biomass increases, then the recipient species may suffer more and experience a decrease in biomass. We chose to use plus signs (+) for the cases where w is negative—i.e., when the source species declines between forecasts which is "good" for the recipient species—and minus signs (−) for the cases where w is positive— i.e., when the source species increases between forecasts which is "bad" for the recipient species—as Kadaba et al. used in their static causal visualizations (Kadaba et al., 2007). Plus signs were drawn in black and minus signs were drawn in white with a black outline to allow for some redundant coding. Several signs are drawn along each arc to allow the user to easily determine the signage of a dynamic arc.

Again, Figure 2-9 shows dynamic arcs that resulted from slightly increasing the fishing effort on elasmobranchs from 1.0 to about 1.25. The spiny dogfish and skate biomasses both

33

decreased as a result of the increase in fishing, as is indicated by the shaded area between the baseline forecast and the current forecast. This is good from the perspective of all of the fish that either spiny dogfish or elasmobranchs predate on or compete with, therefore all of the arcs drawn from these two species show plus signs. For example, spiny dogfish predate on cod, so the arc between them has plus signs. The cod biomass increased, which seems to corroborate with the plus signs drawn on the arc. There are also indirect effects that the arcs help to explain. Cod competes with windowpane, so minus signs are drawn on the arc from cod to windowpane, which helps to explain the slight decrease in the windowpane biomass.

We have realized it is possible for dynamic arcs to be misinterpreted. Users may incorrectly assume that absence of an arc indicates that the relationship is no longer present—e.g., if the predation arc from spiny dogfish to cod is not present, then the spiny dogfish are not eating the cod. However, we believed that users would understand the true meaning of the arcs after a brief explanation—e.g., the arc between spiny dogfish and cod is no longer being drawn because there are no changes in the cod population that might be explained by the spiny dogfish. When informally showing the model to users during and after development, we found that users properly interpreted the arcs after a demonstration or interaction with the model. Another possible criticism of the dynamic arcs is that sometimes many arcs are drawn and it can become cluttered, such as when several sliders are pulled to the extremes. However, generally fewer arcs are drawn in dynamic mode than static mode even in extreme cases. Also, fishery managers may potentially be more interested in comparing the long-term effects of slight adjustments to fishing quota than dramatic adjustments that either eliminate fishing completely or wipe out entire stocks through overfishing.

Dynamic with Animation The third and final type for viewing the inter-species arcs is dynamic arcs with animation, seen in Figure 2-10. In this mode, the rules for the appearance of arcs and their widths is the same as in the non-animated dynamic version. However, the plus (+) or minus (−) signs travel along the arc from the source species to the recipient species. Additionally, the color of the arc alternates between gray and either blue for

34
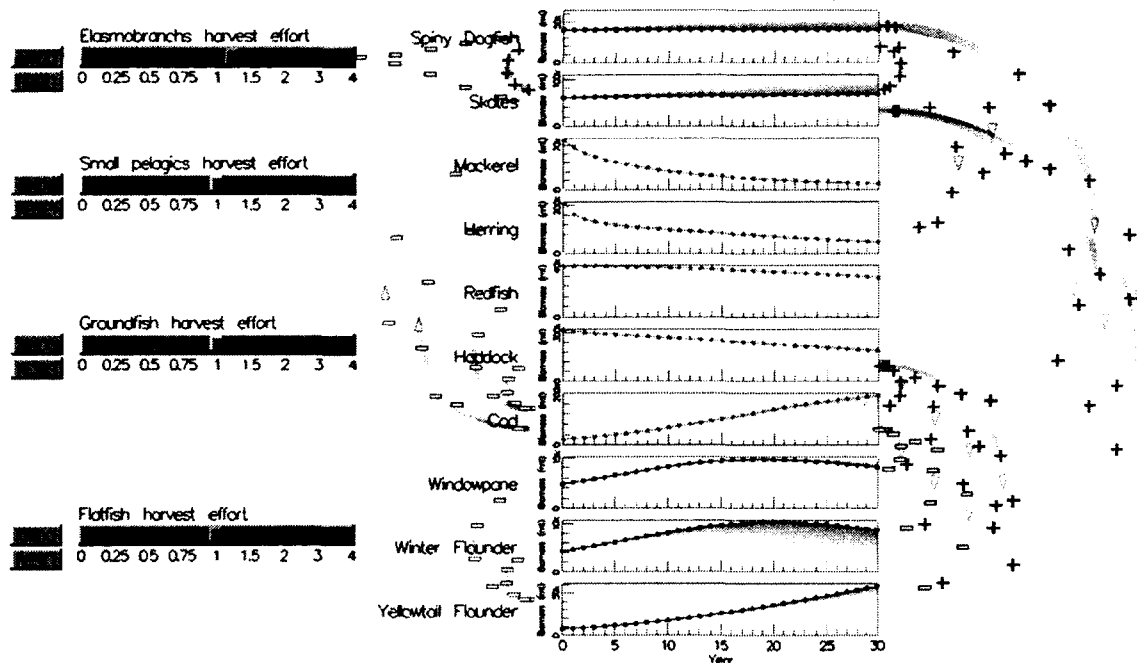
Figure 2-10: The same scenario as in Figure 2-9, though with animated dynamic arcs.

competition or orange for predation. The alteration in color also moves from source to recipient to create a pulsing effect. Both of these cues help to highlight the directionality of the arc.

2.3.2 Harvest Influences

The other type of relationship that must be elucidated by the visualization is the harvest relationship. While it is clear what the harvest effort value is for a particular slider, it could perhaps be clearer which species were directly affected by the harvest and how. Therefore, a spline curve is drawn between a harvest type and a fish species, which correspond to a fishing effort slider and a biomass small multiple, respectively, in the interface. These links are drawn using Hermite spline curves which are colored yellow. There are three styles for determining the width of these spline curves, which correspond to the styles for inter-species arcs: static, dynamic, and dynamic with animation. The controls for setting the inter-species arc style also set the harvest spline curve style.

35
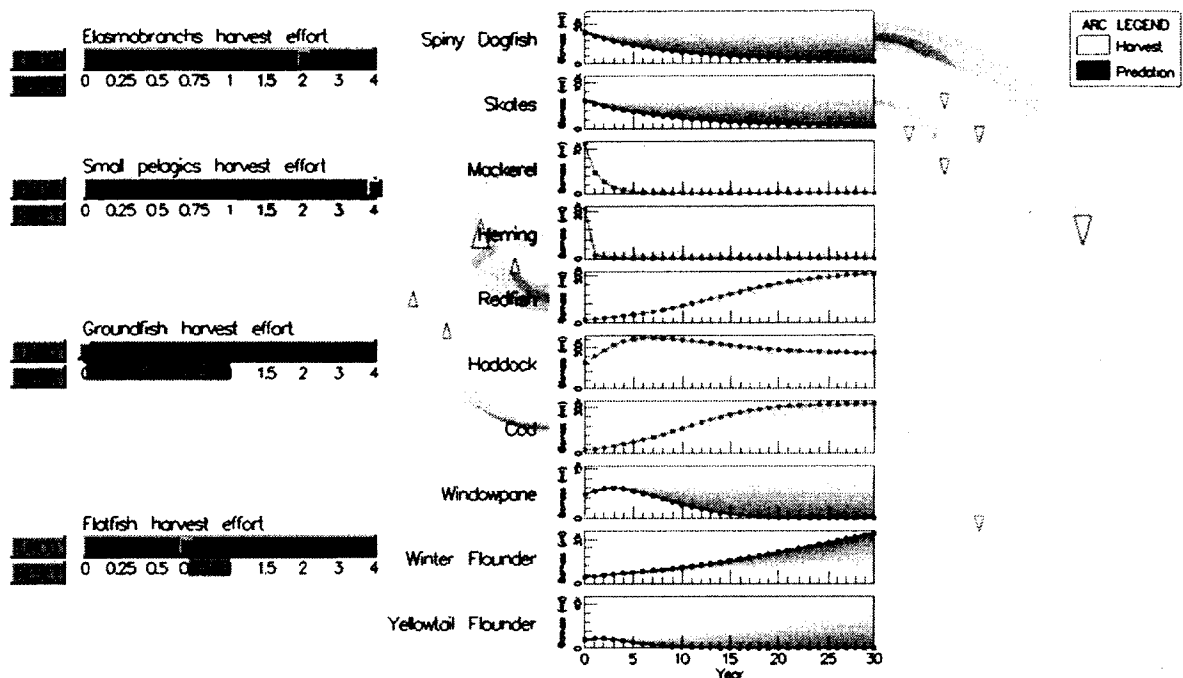
Figure 2-11: Static harvest spline curves in yellow between effort sliders and the small multiples.

Static

In static mode, the harvest spline curve's width is directly proportional to the current value of the harvest slider, as in Figure 2-11. Therefore, when harvest effort for a specific functional group is set to zero (as it is for "Groundfish"), no harvest spline curves are drawn emerging from that harvest effort slider. Likewise, the spline curves are their thickest when the matching effort slider is set to the maximum value of four (as it is for "Small pelagics").

Dynamic

Dynamic harvest splines can be seen in Figure 2-9. The width of a harvest spline in dynamic mode is proportional to the difference between the current value of the effort slider and the baseline value of the effort slider. In other words, the width depends on a weight w:

$$w = E - E' \tag{2.2}$$

36

where E is the current effort and E' is the baseline effort value for the functional group. This is to help highlight and explain the differences between the baseline and current forecasts. Therefore, when the harvest effort for a functional group has not been changed from the baseline, w is zero and no harvest splines are drawn from that functional group's slider.

When $E' > E$ (i.e., when the harvest effort slider has been decreased), w is negative. Therefore, as with dynamic arcs for the inter-species relationships, the harvest splines have signage, which we interpreted from the perspective of the recipient—i.e., the fish being harvested. Thus, when w is negative, black plus signs (+) are drawn along the spline. Conversely, when w is positive, white minus signs (−) are drawn along the spline. From the perspective of the fish, it is "bad" to be fished more and "good" to be fished less. The meaning and design of these signs are the same as for the inter-species arcs.

Dynamic with Animation

Dynamic harvest spline curves, as in Figure 2-10, are drawn following the rules for non-animated spline curves, though with animation added. The animation is similar to the animation for inter-species arcs: the signs travel from the harvest effort slider to the species biomass small multiple chart and the color is alternated with gray to create a pulsing effect. The intent was to give a clearer indication of the direction of the causal relationship.

2.4 Visualization of Uncertainty

Since models are simplifications of reality, their output is best understood as a range of expected values. It is possible that a representation of uncertainty may aid decision making. To add uncertainty visualization to the MS-PROD model, our interface can perform Monte Carlo simulations by randomly varying the non-zero input parameter values ±10% using a normal distribution and computing 100 separate runs of the model. Performing Monte Carlo simulations was necessary because we did not have error estimates for the model.

The resulting uncertainty can be displayed in four styles. First, a multi-line option shows the uncertainty by drawing one semi-transparent line for each run of the Monte Carlo
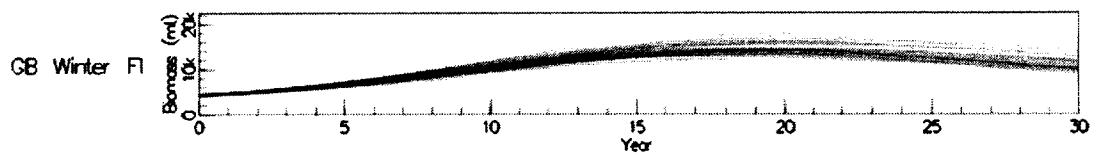
(a) Multi-line.
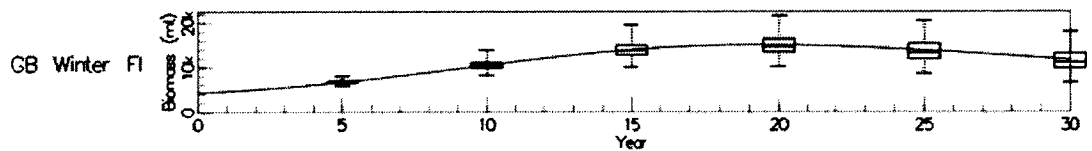
(b) Box plots.
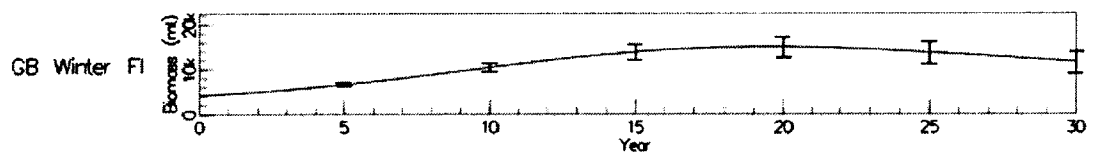
(c) Error bars.
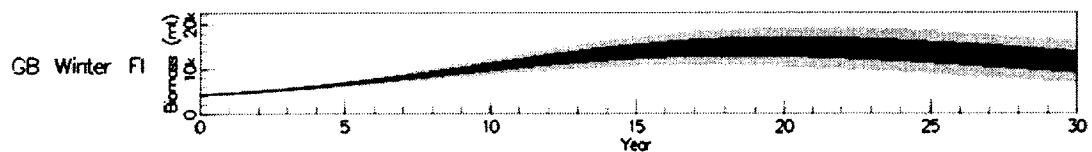
(d) Error bands.

Figure 2-12: The four methods for visualizing uncertainty of MS-PROD model simulations.

38

simulation, as in Figure 2-12(a). This was inspired by Cox et al.'s method for displaying hurricane tracks that is shown in Figure 1-11(b) (2013). The second option displays a traditional box plot every five years, as in Figure 2-12(b). Third, in Figure 2-12(c), a summary line is drawn, with bars every five years. Lastly, Figure 2-12(d) shows a summary line in solid black line with bands.

In all options but the multi-line option, the user has the ability to display different statistical data in the selected style. Users can select between mean and median for the "summary" lines. Box plots, error bars, and error bands can represent either quartiles with minimum and maximum data values or two standard deviations. This allows the user to easily explore the distribution of data under different representations with a few clicks of the mouse. The multi-line option may appeal to less scientific users, while the other more traditional representations of statistical data may appeal to advanced users, such as modelers or fishery managers, but all users have all options at their disposal.

CHAPTER 3

Evaluation

The intention behind this work has been to develop an interactive visualization that effectively portrays the MS-PROD model and its implications. Two types of evaluations were conducted to determine which design alternatives were best for conveying this information: a formal evaluation of the arcs with novice users and an informal evaluation with expert users. These two evaluations and the resulting findings are described in detail below.

3.1 Formal Evaluation of Dynamic Arcs

We were interested in how different visualization alternatives enhance a user's understanding of the complex relationships between the fish species and the effects of those relationships. In other words, is there a benefit to using dynamic, animated arcs—the most complicated representation of the relationships—over another method or even displaying no arcs at all? To investigate this question, we designed and conducted a user study to measure the performance of different arc depiction alternatives. The experimental conditions were as follows:

(A) **No arcs** - Only the time series are displayed on the screen.

(B) **Static arcs** - Arcs are drawn between the time series to show predation or competition. The width of the arc is based on the coefficient in the input parameter file. All arcs are drawn at all times.

(C) **Dynamic arcs without animation** - The arcs change in width according to causal linkage, as described in Section 2.3.1.

(D) **Dynamic arcs with animation** - The arcs are dynamic and feature animation to help indicate the direction of the relationship.

The "blended" depiction of change, shown in Figure 2-5(c), and absolute biomass markers, shown in Figure 2-4, were displayed in all four conditions. Figure 3-1 is an example of the experiment windows as they would appear to a participant performing the study under Condition C.
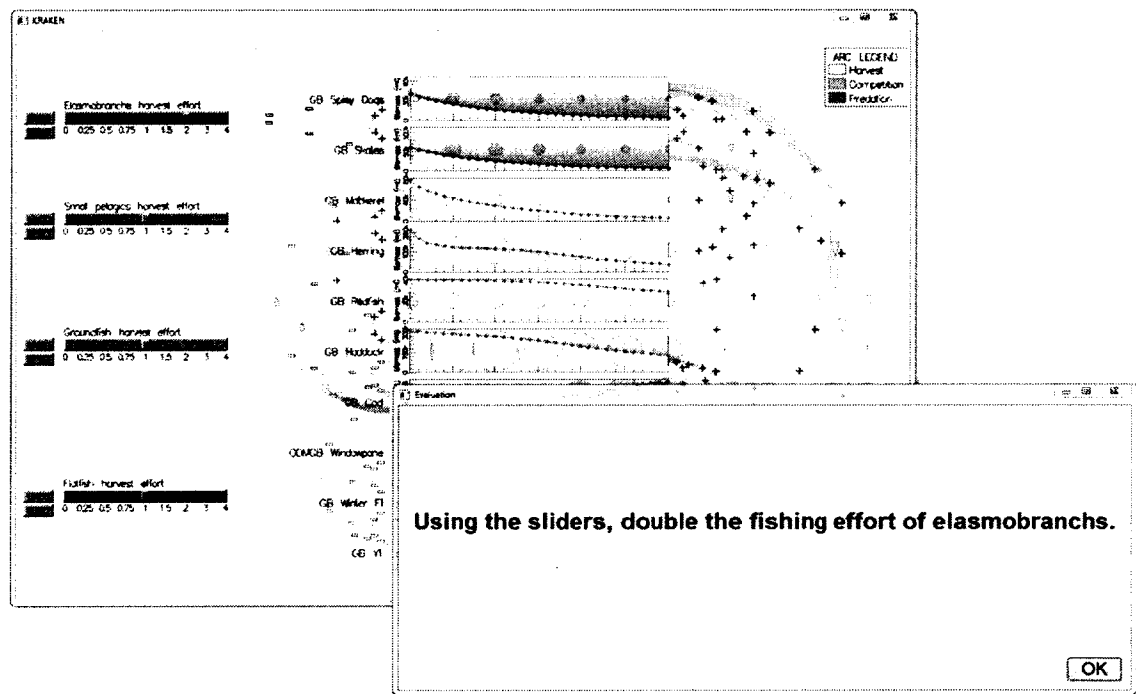
Figure 3-1: An example of the windows seen by the participant during the experiment. The participant is performing the experiment under Condition C (dynamic arcs without animation) and just followed an instruction to double the fishing effort of elasmobranchs.

Our hypothesis was that the Condition A would be the least effective, as it requires the user to guess why indirect or unexpected changes in biomass occurred since no arcs are drawn. We also hypothesized that Conditions C and D would be more effective than Condition B, because dynamic arcs filter to show the relevant information, while static arcs show all information at once which could be overwhelming. Finally, we hypothesized that Condition D would be at least slightly more effective than Condition C, since there are more

41

visual cues for directionality with the animated arcs than with the non-animated arcs.

3.1.1 Method

The study was conducted at a screened-off table in a student union building at the University of New Hampshire. A paid undergraduate research assistant conducted the study and responses from the study were graded by two paid undergraduate research assistants.

Each participant conducted the experiment task for only one of the four conditions. The experiment began with a brief training session which was tailored according to the experimental condition—i.e., arcs were explained only for conditions B, C, and D; the meaning of dynamic arcs were explained only for conditions C and D. Feedback about the quality of the participant's answers was given only during the training phase.

In the remainder of the experiment, the participant followed on screen instructions to manipulate one of the sliders controlling the fish catch. The participant then answered questions about the resulting effects and the reasons for the effects. A single experiment lasted approximately fifteen minutes.

3.1.2 Apparatus

We conducted the experiment using a standard Dell laptop with an extra Dell monitor. The window with the model visualization was maximized on the extra screen, while the window with the experiment questions was maximized on the laptop screen. Participants used the mouse to interact with the model visualization and recorded their answers using the laptop keyboard and mouse.

3.1.3 Participants

There were 80 participants who took part in the study, all of whom were recruited by a poster affixed to the backside of the privacy screen. Participants were randomly assigned to the four conditions, such that there were 20 in each condition. They could have been undergraduate or graduate students; we only required that participants had to be at least

18 years of age. Participants were voluntary and were compensated with a pack of pens or a notebook. They were required to read and sign an Institutional Review Board for the Protection of Human Subjects in Research (IRB) consent form before participating in the study, shown in Appendix C.1.

Participants were asked to provide their gender and their college at the university. There were 28 females and 52 males who took part in the study. There were 31 students from College of Liberal Arts (COLA), 20 from the Peter T. Paul College of Business and Economics, 15 from the College of Life Sciences, eight from the College of Health and Human Services, five from the College of Engineering and Physical Sciences, and one from the Thompson School of Applied Sciences. We created a pseudo-category from the reported colleges based on quantitative skills. Students were placed in the "low quantitative" category if they reported being as a student of COLA and "high quantitative" if the were from any other school. The reasoning was that students in fields such as business, science, and engineering were more likely to have experience reading charts. There were 31 low quantitative students and 49 high quantitative students.

3.1.4 Task

Initially, all fishing effort sliders were set to the value of one. Participants were instructed to increase or decrease the fishing effort of a specific functional group—e.g., *"Using the sliders, double the harvest effort on elasmobranchs."* An example of this type of instructional window as it appeared to participants is shown in Figure 3-2.

Using the sliders, halve the fishing effort of groundfish.
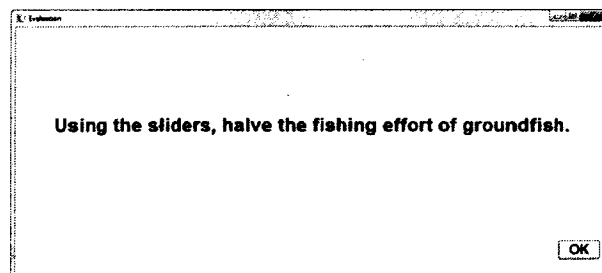
Figure 3-2: An instructional window in the evaluation which guides the participant.
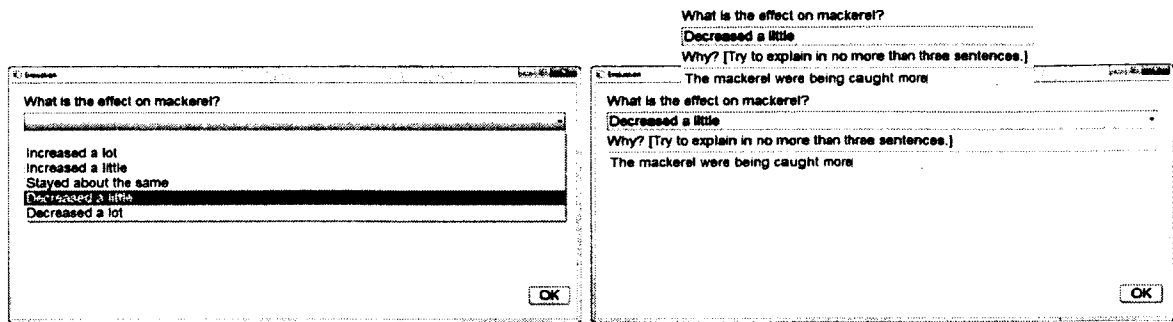
(a) The drop-down for selecting "What...?" an-   (b) The text box for entering "Why?" answers.
swers.

Figure 3-3: Examples of the windows where participants entered answers.

Next, the participants were asked to answer one or more questions of the form, *"What was the effect on (fish species)?"* E.g., *"What was the effect on haddock?"* All questions, as well as their answers, can be seen in Appendix B.2, grouped together by instruction. Participants answered this "What...?" question with one of five options from a drop-down menu:

- *Increased a lot*

- *Increased a little*

- *Stayed about the same*

- *Decreased a little*

- *Decreased a lot*

An example of the evaluation window with the drop-down menu as it appeared to users is shown in Figure 3-3(a).

Finally, the user was asked, *"Why? [Try to explain in no more than three sentences.]"* A large text box was provided for the participant to type a response. This is shown in Figure 3-3(b). If this question was the last question in its set, then the sliders were all reset to one and a new instruction was given for the next set of questions until all questions were answered.

The questions were designed to fit in one of two difficulty categories:

- First-order

- Higher-order

First-order questions asked about a fish species whose biomass changed directly as a result of increased or decreased harvest effort. In other words, the fish was a member of the functional group whose harvest effort was changed and either (a) its biomass decreased due to increased harvest effort or (b) its biomass increased due to decreased harvest effort—e.g., increase harvest on A → biomass of A decreases. There were three "Why?" questions of this type.

Higher-order questions concerned a fish species whose biomass changed from a second-order or third-order effect. In this case, the fish may or may not have been a member of the functional group for which the fishing effort changed. If the fish was a member of the functional group, perhaps its biomass did not change as expected because of the effects of competition or predation with other members of the functional group. If the fish was not a member of the functional group for which fishing effort changed, its biomass may have changed because of competition or predation with a member of that functional group—e.g., increase harvest on A → biomass of A decreases → biomass of B increases because A eats B. More complex explanations involving several inter-species relationships are also possible— e.g., increase harvest on A → biomass of A decreases → biomass of B increases because A eats B → biomass of C decreases because B eats C. There were four higher-order "Why?" questions.

In total, there were three instructions for adjusting the harvest effort and seven pairs of "What?" and "Why?" questions. All participants were given the same instructions and asked the same questions in the same order, regardless of condition.

3.1.5   Results

The answers to the questions of the evaluation were graded on a scale of 0 (i.e., completely wrong) to 3 (i.e., completely correct), with partial points allowed. "What...?" questions, which were answered using a drop-down, were graded automatically by a script, while

45

(a) "What...?" scores. (b) First-order "Why?" scores. (c) Higher-order "Why?" scores.
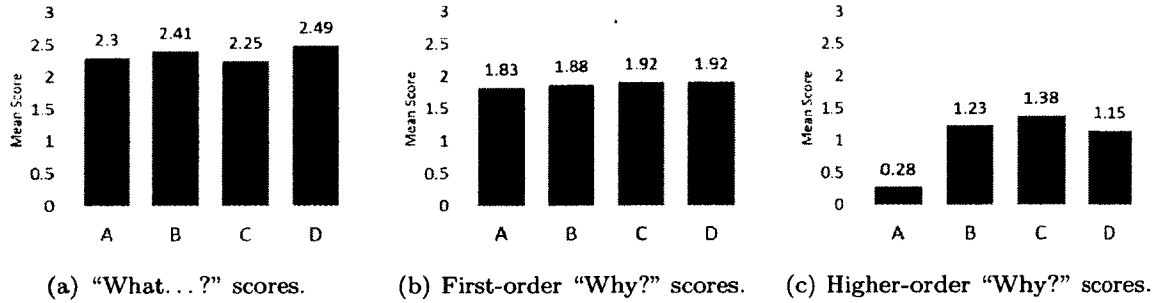
Figure 3-4: Results of the formal evaluation, shown as mean scores graphed by condition. Scores were assigned on a scale from 0 to 3.

"Why?" questions were graded by two undergraduate graders. The average of the two scores was taken and these averages were used in our analyses. The correlation coefficient (Pearson's r) between the scores assigned by the two graders was 0.744.

The summarized results of our evaluation can be found in Figure 3-4, where mean scores are shown by condition. For our analyses, we divided the questions into three categories:

1. "What...?" questions (seven questions)

2. First-order "Why?" questions (three questions)

3. Higher-order "Why?" questions (four questions)

Separate ANOVAs (analysis of variance) were run with Tukey HSD (Honestly Significant Differences) tests for each of these three types of questions. There were no significant differences between the four conditions for the seven "What...?" questions and the three first-order "Why?" questions. However, there was a significant effect for the four conditions with the higher-order "Why?" questions, shown by ($F[1, 76] = 12.6; p < 0.001$) and the HSD test, with no other significant differences (see Figure 3-4(c)).

Additional ANOVAs were run to look for effects of gender and whether the student was a "low quantitative" or "high quantitative" student, as defined in Section 3.1.3. The gender and quantitative factors showed no significant effect for the higher-order "Why?" questions according to our analyses. The quantitative effect, however, approached significance as seen by ($F[1, 3] = 5.26; p = 0.1$); the effects of this are illustrated in Figure 3-5.

46
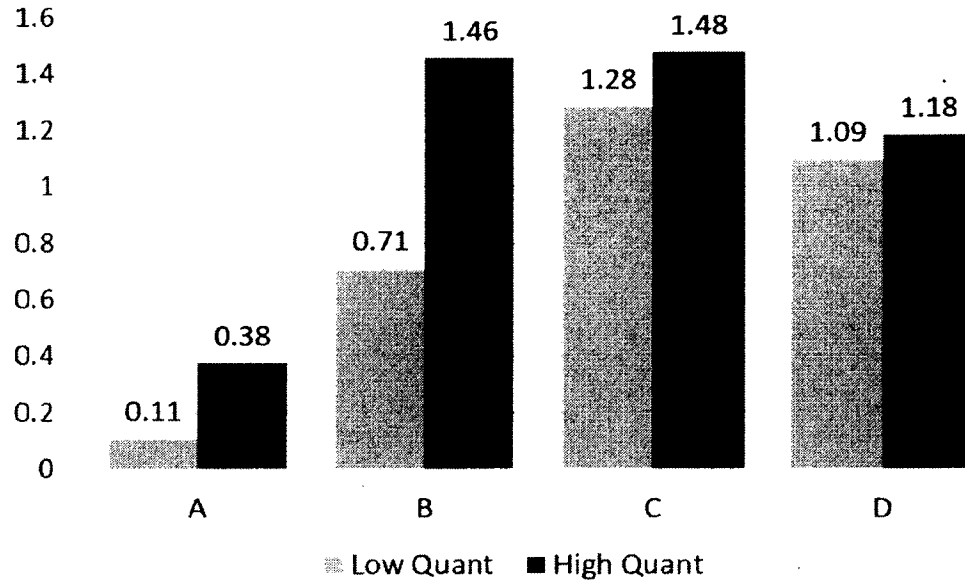
Figure 3-5: Mean scores for low quantitative versus high quantitative students for the higher-order "Why?" questions.

3.1.6 Discussion

Our results strongly suggest that using either static or dynamic arcs is better than using no arcs at all for asking more difficult (i.e., higher-order) questions about the complex, underlying relationships between the species. The presence of causal relationship depiction did not matter when it came to simpler (i.e., "What...?" and first-order "Why?") questions. For the "What...?" questions, this is not surprising, as these questions were concerned with reading a change in a time series chart, for which the inter-species relationships were totally irrelevant. Similarly, the first-order "Why?" questions involved direct effects of the changes in fishing effort, so understanding of the inter-species relationships was unnecessary. Only the higher-order questions involved the competition and/or predation relationships, leading to a significance to the presence or absence of arcs.

Though the difference in mean score between low and high quantitative students, shown in Figure 3-5, failed to reach significance, it is interesting. In Condition A (no arcs), the mean for high quantitative students was over three times the mean for low quantitative students. This could possibly suggest that high quantitative students were able to perform

better in the absence of arcs since they have more experience with quantitative analysis and reasoning. The gap narrowed in the other conditions; under Condition B (static arcs), high quantitative students had scores over twice as high as the low quantitative students on average, while the means were similar in Conditions C (dynamic arcs) and D (animated and dynamic arcs). Again, this effect failed to reach significance, so no strong conclusions should be drawn, but this may imply that dynamic arcs enabled low quantitative students to produce higher quality answers. Perhaps an evaluation with more participants would produce a significant result concerning the type of student.

Despite our efforts to provide a thorough and detailed grading key (see Appendix B.3), the correlation coefficient for the scores assigned by the two undergraduate graders was low. Perhaps the task of assigning scores was difficult due to its subjective nature and the free-form nature of the responses.

3.2   Informal Evaluations

We interviewed three expert users in an informal environment in order to determine their preferences for the alternative depiction of the different features. The informal interviews consisted of explaining and demonstrating the visualization to the participants and asking them to describe which alternative depictions they prefer, if any, and why. Overall, the expert users who participated in the informal evaluations liked the visualization in general, particularly the dynamic, animated arcs. More detailed findings from these informal evaluations are below; the comments were reconstructed from notes made in the meetings.

3.2.1   Michael Fogarty and Robert Gamble

Dr. Michael Fogarty and Robert Gamble—members of the NOAA's National Marine Fisheries Services (NMFS) in Woods Hole, MA—are the original authors of the MS-PROD model with Jason Link. We presented a prototype of the visualization in August 2013 and a more finalized visualization in January 2014. The two of them have been pleased with the visualization.

Before we developed our visualization, they were using Microsoft Excel spreadsheets to graph the CSV output of the model after each run. They reacted positively to the abilities to (a) change fishing effort parameters and see an instantaneous result and (b) easily perceive differences between forecasts that resulted from changes in fishing effort. Dr. Fogarty suggested that the user should be able to set the baseline forecast at any moment, which we implemented. Mr. Gamble expressed interest in keeping all alternative depictions in the final visualization, as he liked the ability to toggle between the various options. He said he could see himself using the small multiples view to understand the relationships between the species, while he might use the four-panel view to prepare figures for future publications.

The feature that Dr. Fogarty and Mr. Gamble have been most enthusiastic about is the dynamic, animated arcs. This feature was first demonstrated at a NMFS meeting on January 24, 2014. Other members in attendance were also excited about the dynamic, animated arcs. Mr. Gamble admitted that the underlying relationships and their counter-intuitive effects sometimes confuse even him. When this happens, he must refer to the predation and competition matrices in the original parameter file to make sense of the confusing results. The dynamic arcs, however, eliminate the need for this extra work by making the relevant relationships more obvious. Members in attendance were very interested in the potential to adapt the visualization to other models. Furthermore, they believed the visualization would allow them to make convincing arguments to fishery managers or other important decision makers to use the MS-PROD model or similar models.

Dr. Michael Fogarty and Robert Gamble have been further developing the MS-PROD model to include types of fishing (e.g., bottom trawl, mid-water trawl, long lines, dredges) with different catchabilities for each pair of fish species and fishing type. They have also introduced climate factors (e.g., average sea floor temperature). They have expressed interest in incorporating these new factors into the visualization, as well as the ability to include more species and/or functional groups. Furthermore, Dr. Fogarty is interested in developing a version of the visualization that is compatible with browsers for usage by the

general public. However, Mr. Gamble expressed reluctance to use the actual names of fish species because this could result in over-interpretation of the results and suggested that generic names like "Elasmobranch 1" and "Elasmobranch 2" be used.

In general, Dr. Fogarty and Mr. Gamble were satisfied with the quality of the visualization. Mr. Gamble said that he was not sure how to express what he wanted in a visualization when our collaboration began, but he saw what he had originally envisioned when he saw the finalized visualization.

3.2.2 David Goethel

On April 1, 2014, we conducted an informal interview with David Goethel. David Goethel is a biologist and fisherman based out of Hampton, New Hampshire, who has advised several state and federal fishery management boards and served on the New England Fishery Management Council. As a fisherman, he catches all ten of the species used in the MS-PROD model throughout the year, as well as others. He has been an advocate for moving toward a more sustainable approach to fishery management and is interested in models that can help illustrate that change is necessary.

Mr. Goethel found both the small multiple and four panel views useful. He did not have a preference over either view and said that he might choose which one to use depending on his intended audience or what he was investigating in the model. Similarly, he said he liked all options for uncertainty visualization and would choose based on his audience; he might use error bands when presenting to the general public, but use box plots for fishery managers. He had previously believed that stock assessments should be presented more like hurricane tracks, with multiple forecasts to show multiple opinions, therefore he found the range of forecasts shown in the uncertainty view to be particularly helpful.

As for the different depictions of change, Mr. Goethel preferred the blended, shaded area between the two forecasts over instantaneous change only or the dotted line for the previous forecast. He said he would always use the blended option because it was more informative. For understanding the relationships between fish, he preferred the dynamic,

animated arc over all other options. This option allows the user to "follow the flow [of the relationships] more easily," while he found it "harder to see the conclusion" of the effects of the harvest without animation. He was excited to see a visualization of these relationships because they can be counter-intuitive even to someone with as much experience as he has.

Overall, Mr. Goethel was interested in the model, saying that its visualization would help to convince people that more complex models like MS-PROD are necessary. He said fishery managers typically prefer single species models and make decisions for ten-year periods. However, Mr. Goethel finds it important to consider multiple species as well as other factors and to think about management for longer time periods, like MS-PROD does. He said that MS-PROD "might reflect reality more," and our visualization might help to persuade managers of this. He recommended restricting access to the model to the scientific community only for now and waiting before presenting it to the general public to avoid unexperienced users from drawing incorrect conclusions.

CHAPTER 4

Conclusion

4.1   Conclusions

A long-term goal of this thesis has been to help the fishery management community make informed decisions with the use the MS-PROD model through our interface. Declaring whether we achieved this long-term goal requires public unveiling of the MS-PROD model by its original authors and time to determine if it actually benefits managers, fishermen, and other significant stakeholders. Therefore, no conclusion can be drawn yet for this goal. On the other hand, the short-term goal of this thesis has been to develop an interactive visualization that would enhance understanding of a complicated, multi-species production model, MS-PROD. More specifically, we investigated the effectiveness of different methods for depicting causal relationships. Our informal interviews with expert users led us to believe we had succeeded in creating a visualization to their satisfaction. However, to measure this objectively, we conducted an evaluation of the different depictions of the predation and competition relationships between the ten key species of the MS-PROD model.

Our evaluation of the depictions of the inter-species relationships showed that having arcs is superior to no arcs for answering higher-order questions about changes in biomass. This was not surprising, since no arcs is uninformative and the higher-order questions involved complex, indirect effects from changes in fishing effort. A visualization of the arcs was essential to answer these types of questions. More investigation is necessary to find significant differences between the different types of arcs—i.e., static, dynamic, and animated dynamic.

Additionally, our visualization contributes to the community of modeling in general. Our interface is a novel combination of time series, a network diagram, interactions, and the

model itself. These combined elements allow users to not only compare differences between two forecasts as in a traditional spreadsheet model, but also to understand what factors account for these differences, leading to a better understanding of the model in general. The ability to correctly interpret a model is crucial for users of all levels of expertise, since models can easily become complicated as more factors are incorporated in order to make the model more accurate. We believe our visualization approach might be a powerful tool for other ecological models or even models in other fields such as economics, medicine, engineering, and so on.

4.2   Future Work

Most immediately, we are curious to see if a larger study of the different depictions of the causal relationships would yield more significant results. In particular, we would hope to see a major difference between static and dynamic arcs. Besides recruiting more participants and perhaps restructuring the questions to be asked, we could also explore alternative depictions of the causal relationships. With dynamic arcs, we were attempting to encode for causal relationships that might explain differences between forecasts. Different equations to determine the widths of these dynamic arcs could have been investigated. Furthermore, the arcs themselves could have been drawn differently to more precisely describe the differences between forecasts—e.g., colors or drawing styles could have been varied to show how the arc grew or shrank instead of using plus signs or minus signs.

Concerning the model itself, there are many possible directions this research could take in the future. The visualization could be adapted to newer versions of the MS-PROD model which incorporate more ecological factors, such as climate, and more realistic simulations of harvest, which include many types of fishing gear and catchabilities for each fish species for each fishing gear. Future versions of MS-PROD may also include spatial information, which would also require further expansion of our visualization. Researchers at NOAA's National Marine Fisheries Services also expressed interest in adapting the visualization to other models. The visualization was implemented to be as agnostic to the model as

possible, but more work might be necessary to allow for easy addition of new features and to allow other models to be used in place of MS-PROD. However, a more generic version of the visualization would be a powerful tool which many scientists, modelers, and ecologists might be interested in using.

More work would be required in order to increase the scalability of the visualization. A model might represent an ecosystem of twenty species, which might require a whole new approach since arc diagrams are better suited to smaller datasets. Perhaps a traditional node-link diagram could be used where the node for each fish species is a compact time series chart. For much larger datasets (e.g. fifty or more), the user would need a mechanism to view subsets of the data to avoid being overwhelmed from seeing the entire dataset at once, such as zooming, pop-up windows, a fisheye navigation, or an "expand and collapse" feature.

Finally, Dr. Michael Fogarty and Robert Gamble—who developed the MS-PROD model with Jason Link—are interested in adapting the visualization to be more accessible by the general public. The most simple way to do this would be to allow users to download an executable of the visualization from the web which could be run on a local machine. However, a more effective—though time-consuming—approach would be to develop a version of the visualization which can easily be run in a browser, because casual users might be less inclined to download an executable. This second approach would require reimplementation in a browser-friendly language such as JavaScript. For either approach, both Dr. Fogarty and Gamble are reluctant to allow for actual species names to be shown in case the results are over-interpreted. They recommend that more abstract names such as "Small Pelagic 1" or "Elasmobranch 2" be used.

4.3 Summary

Fisheries management, which is the science of setting rules for governing fishing, is necessary to ensure we are exploiting our oceans sustainably. The fishery managers have a difficult job since their only action is to set fishing quotas, but ecological models can help

by attempting to predict the consequence of their decisions in advance. We must move toward ecosystem-based fisheries management by considering as many ecological factors as possible. MS-PROD is a step in the right direction because it simulates the effects of competition, predation, and harvest on ten key species in the Gulf of Maine. Our visualization of MS-PROD makes the model more accessible to a wider audience. The unique combination of time series, a network diagram, user interactions, and the MS-PROD model itself allow for quick and easy usage of the model. Our evaluation found that arc diagrams enhanced understanding of the complex inner workings of the model. We hope that our visualization of MS-PROD will go on to assist fishery managers with their decisions and possibly contribute to future generations also enjoying usage of our oceans.

BIBLIOGRAPHY

Dan Bricklin and Bob Frankston. VisiCalc: Information from its creators, Dan Bricklin and Bob Frankston. http://bricklin.com/visicalc.htm, 1999. [Online; accessed 2013-10-07].

Norman L. Christensen, Ann M. Bartuska, James H. Brown, Stephen Carpenter, Carla D'Antonio, Rober Francis, Jerry F. Franklin, James A. MacMahon, Reed F. Noss, David J. Parsons, Charles H. Peterson, Monica G. Turner, and Robert G. Woodmansee. The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications*, 6(3):665–691, August 1996. ISSN 10510761.

William S. Cleveland, Marylyn E. McGill, and Robert McGill. The shape parameter of a two-variable graph. *Journal of the American Statistical Association*, 83(402):289–300, 1988. ISSN 01621459.

Jonathan Cox, Donald House, and Michael Lindell. Visualizing uncertainty in predicted hurricane tracks. *International Journal for Uncertainty Quantification*, 3(2):143–156, 2013. ISSN 2152-5080.

Robert L. Eberlein and David W. Peterson. Understanding models with Vensim^{TM}. *European Journal of Operational Research*, 59(1):216–219, May 1992.

Sarah K. Gaichas and Robert C. Francis. Network models for ecosystem-based fishery analysis: a review of concepts and application to the Gulf of Alaska marine food web. *Canadian Journal of Fisheries and Aquatic Sciences*, 65(9):1965–1982, 2008.

Robert J. Gamble and Jason S. Link. Analyzing the tradeoffs among ecological and fishing effects on an example fish community: A multispecies (fisheries) production model. *Ecological Modelling*, 220(19):2570–2582, 2009. ISSN 0304-3800.

Mohammad Ghoniem, Jean-Daniel Fekete, and Philippe Castagliola. A comparison of the readability of graphs using node-link and matrix-based representations. In *Proceedings of the IEEE Symposium on Information Visualization*, INFOVIS '04, pages 17–24, Washington, DC, USA, 2004. IEEE Computer Society. ISBN 0-7803-8779-3.

B. Grad. The creation and the demise of VisiCalc. *Annals of the History of Computing, IEEE*, 29(3):20–31, 2007. ISSN 1058-6180.

S. Havre, B. Hetzler, and L. Nowell. ThemeRiver: visualizing theme changes over time. In *IEEE Symposium on Information Visualization*, pages 115–123, 2000.

Jeffrey Heer, Michael Bostock, and Vadim Ogievetsky. A tour through the visualization zoo. *Commun. ACM*, 53(6):59–67, June 2010. ISSN 0001-0782.

Danny Holten and Jarke J. van Wijk. A user study on visualizing directed edges in graphs. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 2299–2308, New York, NY, USA, 2009. ACM. ISBN 978-1-60558-246-7.

G. J. Hunter and M. F. Goodchild. Managing uncertainty in spatial databases: Putting theory into practice. *URISA*, pages 1–14, 1993.

Waqas Javed, Bryan McDonnel, and Niklas Elmqvist. Graphical perception of multiple time series. *IEEE Transactions on Visualization and Computer Graphics*, 16(6):927–934, November 2010. ISSN 1077-2626.

Nivedita Kadaba, Pourang Irani, and Jason Leboe. Visualizing causal semantics using animations. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1254–1261, 2007. doi: 10.1109/TVCG.2007.70618.

Donald E. Knuth. *The Stanford GraphBase: a platform for combinatorial computing*. ACM, New York, NY, USA, 1993. ISBN 0-201-54275-7.

P. H. Leslie and J. C. Gower. The properties of a stochastic model for the predator-prey type of interaction between two species. *Biometrika*, 47:219–301, 1960.

Alfred J. Lotka. The frequency distribution of scientific productivity. *Journal of the Washington Academy of Sciences*, 16(12):317–323, 1926.

Albert Michotte and Georges Thinés. La causalité perceptive. *Journal de Psychologie Normale et Pathologique*, pages 9–36, 1963.

United States. National Marine Fisheries Service. Ecosystem Principles Advisory Panel. *Ecosystem-based fishery management: a report to Congress*. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 1999.

William Playfair. *The Commerical and Political Atlas: Representing, by means of stained copper-plate charts, the progress of the commerce, revenues, expenditure and debts of England during the whole of the Eighteenth Century*. 1786.

Kristin Potter, Joe Kniss, Richard Riesenfeld, and Chris R. Johnson. Visualizing summary statistics and uncertainty. *Computer Graphics Forum (Proceedings of Eurovis 2010)*, 29 (3):823–831, 2010.

M. L. Rosenzweig and R. H. MacArthur. Graphical Representation and Stability Conditions of Predator-Prey Interactions. *The American Naturalist*, 97(895):209+, January 1963.

Takafumi Saito, Hiroko Nakamura Miyamura, Mitsuyoshi Yamamoto, Hiroki Saito, Yuka Hoshiya, and Takumi Kaseda. Two-tone pseudo coloring: Compact visualization for one-dimensional data. *IEEE Symposium on Information Visualization*, 0:23, 2005. ISSN 1522-404x.

Milner B. Schaefer. A study of the dynamics of the fishery for yellowfin tuna in the eastern tropical pacific ocean. *Inter-American Tropical Tuna Commission Bulletin*, 2(6):243–285, 1957.

Lisa Tweedie, Robert Spence, Huw Dawkes, and Hua Su. The influence explorer. In Jim Miller, Irvin R. Katz, Robert L. Mack, and Linn Marks, editors, *CHI 95 Conference Companion*, pages 129–130. ACM, 1995.

Vito Volterra. Fluctuations in the abundance of a species considered mathematically. *Nature*, 118:558–560, 1926.

Colin Ware. Perceiving complex causation through interaction. In *Proceedings of the Symposium on Computational Aesthetics*, CAE '13, pages 29–35, New York, NY, USA, 2013. ACM. ISBN 978-1-4503-2203-4.

Colin Ware, Eric Neufeld, and Lyn Bartram. Visualizing causal relations. *IEEE Symposium on Information Visualization: Late Breaking Hot Topics*, pages 39–42, 1999.

Martin Wattenberg. Arc diagrams: Visualizing structure in strings. In *Proceedings of the IEEE Symposium on Information Visualization*, INFOVIS '02, pages 110–116, Washington, DC, USA, 2002. IEEE Computer Society. ISBN 0-7695-1751-X.

M. Weber, M. Alexa, and W. Muller. Visualizing time-series on spirals. In *IEEE Symposium on Information Visualization*, pages 7–13, 2001.

Appendices

Appendix A

MS-PROD Input Parameters

The following are the input parameter values used for the development and evaluation of our visualization to the MS-PROD model. These values were given to us by one of the model authors, Robert Gamble, and were unchanged except for catchability and effort. In MS-PROD, effort (E) and catchability (q) can be set to different values for each of the thirty years for each species, but we kept these values the same across all years to simplify the controls needed to interact with the model. Some terms have been abbreviated to allow these tables to fit; the abbreviations are defined following the tables. Additionally, the names of the species did not fit into the coefficient matrices, therefore letters were assigned to each species in the first table for use in subsequent tables.

Species	Guild	N_0	K	r	q	E	Dem.	Pel.
(a) Yellowtail Fl.	F	8000	230000	0.66	0.1	1	1	0
(b) Cod	G	22563	700000	0.64	0.22	1	1	0
(c) Haddock	G	316000	700000	0.52	0.28	1	1	0
(d) Winter Fl.	F	4301	230000	0.74	0.3	1	1	0
(e) Windowpane	F	7288	230000	0.6	0.25	1	1	0
(f) Redfish	G	40048.8	700000	0.232	0.2	1	1	0
(g) Herring	SP	209400	350000	0.62	0.24	1	0	1
(h) Mackerel	SP	77600	350000	0.32	0.14	1	0	1
(i) Skates	E	60683	450000	0.2	0.13	1	1	0
(j) Spiny Dogfish	E	40000	450000	0.2	0.13	1	1	0

A.1 Competition Coefficient Matrix

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
on (a)	0	0.05	0.424	0.3	0.4	0.076	0	0	0.3	0
on (b)	0.12	0	0.5	0.05	0.12	0.276	0	0	0.01	0.05
on (c)	0.3	0.6	0	0.2	0.15	0.125	0	0	0.2	0.1
on (d)	0.5	0.101	0.141	0	0.4	0.041	0	0	0.6	0.4
on (e)	0.32	0.248	0.233	0.18	0	0.219	0	0	0.2	0
on (f)	0.119	0.3	0.132	0.12	0.15	0	0	0	0.1	0.2
on (g)	0	0	0	0	0	0	0	0.4	0	0
on (h)	0	0	0	0	0	0	0.6	0	0	0
on (i)	0	0	0	0	0	0	0	0	0	0.5
on (j)	0	0	0	0	0	0	0	0	0.8	0

A.2 Predation Coefficient Matrix

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
on (a)	0	7E-08	0	0	0	0	0	0	0	0
on (b)	0	0	0	0	0	0	0	0	0	3E-06
on (c)	0	0	0	0	0	0	0	0	0	0
on (d)	0	0	0	0	0	0	0	0	0	0
on (e)	0	0	0	0	0	0	0	0	0	0
on (f)	0	0	0	0	0	0	0	0	0	0
on (g)	0	1E-06	0	0	0	1E-06	0	0	1E-06	1E-06
on (h)	0	4E-07	0	0	0	3E-06	0	0	1E-07	4E-07
on (i)	0	0	0	0	0	0	0	0	0	0
on (j)	0	0	0	0	0	0	0	0	0	0

A.3 Abbreviation Key

Fl.	Flounder
E	Elasmobranchs
F	Flatfish
G	Groundfish
SP	Small pelagics
N_0	initial biomass
K	carrying capacity
r	growth rate
q	catchability
E	effort
Dem.	demersal
Pel.	pelagic

Appendix B

Formal Evaluation

B.1 Protocol

B.1.1 Abstract

MS-PROD is an ecological fisheries model which models the biomass of fish over 30 years. In the model, the biomass of each fish species depends on effects from harvesting and interactions with the other fish species. Therefore, the visualization of this model requires representations for the biomass as well as the different inter-species relationships that impact the biomass. We represent the biomasses over time with time series and the relationships with links between the different time series charts. Users can interactively change the fishing levels to understand what fish species will be affected and why. The purpose of this study is to explore the extent to which different depictions of inter-species relationships help to explain the complex inter-species relationships in an understandable manner.

B.1.2 Key

Here is a key for the different types of text in the Script and Training Example sections:

- *Italic text indicates an instruction to the evaluation proctor.*

- *Italic underlined text indicates an instruction to stop or start reading the instructions based on the experimental condition.*

- Normal text indicates something the evaluation proctor should say out loud to the participant.

B.1.3 Conditions

There are four conditions in the experiment:

(A) No between-species links

(B) Static between-species links

(C) Dynamic between-species links

(D) Dynamic, animated between-species links

B.1.4 Script

[*Run KRAKEN.exe and click the "RUN" button. Select the condition for the participant using the drop-down menu.*]

Here we have a visualization for a model called MS-PROD, which predicts the effects of fishing on ten species, while also taking into account how the fish affect each other. The purpose of this visualization is to help people understand how fishing impacts the fish over a few decades.

MS-PROD is a mathematical model which makes 30-year biomass forecasts for ten species of fish. Here you can see there are ten charts, one for each fish species. [*Point to the ten charts.*]

We have time, measured in years, on the x-axis and biomass on the y-axis. [*Point to the x-axis of the bottom-most chart.*] Biomass is the amount of a species in an ecosystem at a time, measured in Megatons.

Since biomasses vary between species, each fish species has its own chart with its own y-axis scale. [*Motion to the different y-axes scales.*] Therefore, these gray circles show the absolute size of the biomass to allow for comparisons between species. [*Motion to the gray biomass indicators.*]

The biomass of an individual species is predicated by the MS-PROD model according to a few factors:

- growth of the species,

- losses due to harvesting by humans, and

- losses due to interactions with the other nine species

These ten species are divided into four functional groups. A functional group is a biological grouping of species that perform similar functions within their ecosystem. We have colored and positioned the ten species according to the functional groups [*point toward each functional group*]:

- Elasmobranchs

- Small pelagics

- Groundfish

65

• Flatfish

The fish are harvested according to functional group. The sliders on the left-hand side represent the harvest effort for each functional group. [*Point to the sliders.*] The harvest effort represents how hard the fishermen are trying to catch the fish in that group. Right now, all of the sliders are set to one.

Changing a slider causes the model to instantaneously recalculate the biomass forecasts. You can increase how hard the fishermen are trying by pulling the slider to the right and decrease by pulling to the left. [*Slowly pull the groundfish slider (green) down to 0.75 and up to 1.5. Leave it at 1.5.*]

We have drawn a shaded "ghost" to help you compare the current forecast with a "baseline" forecast. The "baseline" forecast is from when all of the harvest efforts were set to one. The "ghost" is drawn above or below the current forecast, extending toward the baseline forecast.

[*Motion to the large shaded area on the cod plot.*] This shaded area shows us that cods biomass has decreased from the baseline forecast.

[*Motion to the blue rectangle under the slider.*] This marker helps us keep track of where the effort was before we changed it. [*Click the "RESET" button next to the groundfish slider.*]

[*Click "OK" in the experiment window.*]

[*Condition A ends here; resume at **Training Example***]

Before we mentioned that species face losses due to either harvesting from humans or because of interactions with other fish. There are two types of interactions that occur between species:

- predation, which is when one species is consumed by another species, [*motion to the orange arrows going between some of the charts*] and

- competition, which is when one species suffers due to its resources being consumed or utilized by another species [*motion to the blue arrows going between some of the charts*]

These semi-circle links going between the charts indicate the presence of one of these relationships between two species. The width of these links represents the strength of the relationship; wider links means the recipient species is impacted heavily by the source species.

The direction of the links is indicated by the triangle in the middle. For example, Spiny Dogfish eat cod. [*Hover over the Spiny Dogfish to Cod link, which is the largest orange one on the right.*] Additionally, the links are drawn clockwise, so the arrows on the right-hand side can be read top-to-bottom and the arrows on the left-hand side can be read bottom-to-top.

[*Conditions C and D continue*]

However, there are many links being drawn here. Instead, we can draw the links selectively.

[*Slowly pull the groundfish slider (green) again down to 0.75 and up to 1.5.*]

Now, the links are only being drawn to explain the differences between the baseline forecast and the current forecast. A link grows as that relationship becomes more relevant in explaining the differences when the two forecasts. If a link isn't relevant at all, then the link isn't shown.

A link disappearing does not mean the relationship isn't part of the model anymore. It simply means that relationship does help to explain the changes from the baseline to the current forecast.

There are plus and minus signs drawn to indicate the nature of the relationship from the perspective of the recipient species.

For example, if a predator species is fished more, then this is good from the perspective of a prey species, because there are less of the predator eating the prey. In this situation, you would see a plus sign drawn on the arc from the predator to the prey.

A predator being fished less is bad from the perspective of the prey, because then the prey will be eat more. In this case, you would see a minus sign drawn on the arc from the predator to the prey.

Similarly, plus and minus signs are drawn on the links between the sliders and fish charts, to show the perspective of the fish on the change in effort.

[*Click "OK" in the experiment window.*]

[*Conditions C and D end here; resume at* **Training Example**]

B.1.5 Training Example

[*ALL conditions resume here*]

In this evaluation, we will have you increase or decrease a specific harvest effort and then explain the changes you observe. We will go through a training example which is similar to the questions you'll be asked.

[*Give the participant control of the mouse.*]

Using the sliders, halve the fishing effort of groundfish.

Notice that the redfish, haddock, and cod biomasses increased due to decreased harvesting of groundfish. That is, the shaded region shows how the current forecast compares with the baseline forecast.

Notice that the biomass of other fish species changed as well, such as mackerel. Next, you will answer a question that is similar to the experiment questions.

Q1: What is the effect on mackerel? Q2: Why?

[Allow the participant to answer the question.]

[*Condition A*]

A1: Mackerel decreased a little.

A2: Interactions between the species must explain why mackerel decreased. Perhaps one of the groundfish species eats or competes with mackerel.

[*Conditions B, C, and D*]

A1: Mackerel decreased a little.

A2: Redfish eat mackerel. The decreased harvest on groundfish caused an increase in the redfish biomass. There were more redfish to predate on the mackerel, so the mackerel suffered.

Extra explanation: Notice the orange arrow going from redfish to mackerel. This indicates redfish eat mackerel. We halved the harvest of groundfish, so the biomass of redfish increased. Since the redfish biomass increased, more mackerel were being consumed. This could explain the decreased mackerel biomass.

[*Training example ends here; evaluation begins*]

B.2 Questions and Answers

Our evaluation featured a window which displayed the questions with drop-downs and text boxes for the participants to enter answers. The questions that were displayed to the participants are below, with correct answers indicated in red italics.

(A) Double the harvest effort on **small pelagics**.

1. *[First-order]*

    i. What is the effect on **herring**? *Decreased a little.*

    ii. Why? *The fishing effort increased, so more herring are caught, resulting in a smaller biomass for herring over time.*

(B) Halve the harvest effort on **flatfish**.

2. *[First-order]*

    i. What is the effect on **winter flounder**? *Increased a lot.*

    ii. Why? *Winter flounder is a flatfish, so fishing less for flatfish results in an increased biomass for winter flounder.*

3. *[Second-order]*

    i. What is the effect on **yellowtail flounder**? *Stayed about the same.*

    ii. Why? *One would expect the biomass of yellowtail flounder to increase due to halving the flatfish fishing effort. However, both windowpane and winter flounder, both flatfish, compete with yellowtail flounder. Their increased biomass seems to have prevented the yellowtail flounder biomass from increasing much.*

(C) Double the harvest effort on **elasmobranchs**.

4. *[First-order]*

    i. What is the effect on **skates**? *Decreased a lot.*

70

ii. **Why?** *Skates are elasmobranchs, so fishing more for elasmobranchs resulted in a decrease in biomass.*

5. *[Second-order]*

i. **What is the effect on cod?** *Increased a lot.*

ii. **Why?** *Spiny dogfish, which are elasmobranchs, predate on cod. Doubling the harvest on elasmobranchs caused the biomass of spiny dogfish to decrease. Since there were less spiny dogfish to predate on the cod, the cod biomass increased.*

6. *[Third-order]*

i. **What is the effect on haddock?** *Decreased a lot.*

ii. **Why?** *Spiny dogfish, which are elasmobranchs, predate on cod. The decrease in elasmobranchs caused an increase in cod. Cod compete with haddock, so the increase in cod led to a decrease in haddock.*

7. *[Third-order]*

i. **What is the effect on windowpane?** *Decreased a lot.*

ii. **Why?** *Spiny dogfish predate on cod, so the increased harvest on elasmobranchs led to the cod biomass increasing. Cod compete with windowpane, so the windowpane biomass suffers due to the increased cod biomass.*

B.3 Grading Scheme

B.3.1 Note to Graders

- The "What is the effect on ____?" questions are graded automatically.

- The "Why?" questions are graded on a scale of 0 to 3 (partial points allowed). Examples and explanations of the answers are listed below.

- Assign grades without considering the condition the participant was assigned.

B.3.2 Point Value Explanation

Score	Meaning
0	Completely wrong
1	More wrong than right
2	More right than wrong
3	Completely correct

B.3.3 Grading Key

1. i. What is the effect on **herring**?

Answers	Score
Decreased a lot	2
Decreased a little	3
Stayed about the same	1
Increased a little	0
Increased a lot	0

ii. Why?

Score	Example	Description
3	Herring are small pelagics, so they are being caught more when small pelagic fishing effort increases, therefore their biomass decreases.	Mentions that herring are being **caught more** (since herring are small pelagics).
2	More small pelagics are being caught.	Mentions small pelagic fishing effort increased without indicating that this means more herring were being caught.
1	We are fishing for herring.	Generic statement like "Harvesting increased" or something which implies we were not fishing for herring before.
0	Since we are harvesting more small pelagics, there are less for the herring to eat.	Something false, confusing, irrelevant, etc.

2. i. What is the effect on **winter flounder**?

Answers	Score
Decreased a lot	0
Decreased a little	0
Stayed about the same	0
Increased a little	1
Increased a lot	3

ii. Why?

Score	Example	Description
3	Winter flounder are flatfish, so they are being caught less due to the decreased harvest effort of flatfish, therefore their biomass increases.	Mentions that winter flounder are being **caught less** (since winter flounder are flatfish).
2	Less flatfish are being caught.	Mentions flatfish fishing effort decreased without indicating that this means more winter flounder were being caught.
1	Harvest decreased.	Generic statement that is true but does not make a conclusion.
0	We are not fishing for winter flounder.	Something false, confusing, irrelevant, etc.

3. i. What is the effect on **yellowtail flounder?**

Answers	Score
Decreased a lot	0
Decreased a little	0
Stayed about the same	3
Increased a little	2
Increased a lot	0

ii. Why?

Score	Example	Description
3	Winter flounder and windowpane, the other flatfish, both compete with yellowtail flounder. They both grew because of the decreased effort on flatfish. Their increase in biomass led to increased competition on yellowtail flounder, which prevented growth of the yellowtail flounder.	Mentions that windowpane and winter flounder **compete** with yellowtail flounder. Mentions their biomass increased, which made the effects of competition more pronounced.
2	It stayed about the same because there was a lesser effort in catching fish, and because both compete with yellowtail flounder.	Blames competition without clearly saying who is competing with the yellowtail flounder or mentions that some fish compete with the yellowtail flounder without mentioning that those fish had an increase in biomass.
1	It appears that the yellow flounder is not affected as much by a change in fishing rates.	Generic statement that is true but does not make a conclusion.
0	Yellowtail and haddock populations both remained stable, so the balance was unchanged.	Something false, confusing, irrelevant, etc.

4. i. What is the effect on **skates**?

Answers	Score
Decreased a lot	3
Decreased a little	1
Stayed about the same	0
Increased a little	0
Increased a lot	0

ii. Why?

Score	Example	Description
3	Skates are elasmobranchs. Since the harvest effort increased on elasmobranchs, skates are being harvested more and their biomass decreased.	Mentions that skates are being **caught more** (since skates are small pelagics).
2	We are harvesting more elasmobranchs.	Mentions elasmobranch fishing effort increased without indicating that this means more skates were being caught.
1	We doubled the harvest effort.	Generic statement like "Harvest increased" or "We are fishing for skates" (implying that we were not fishing for them before).
0	Skates compete with spiny dogfish.	Something false, confusing, irrelevant, etc.

5. i. What is the effect on **cod**?

Answers	Score
Decreased a lot	0
Decreased a little	0
Stayed about the same	0
Increased a little	1
Increased a lot	3

ii. Why?

Score	Example	Description
3	Spiny dogfish, which are elasmo-branchs, predate on cod. Doubling the harvest on elasmobranchs caused the biomass of spiny dog-fish to decrease. Since there were less spiny dogfish to predate on the cod, the cod biomass increased.	Mentions that spiny dogfish, which are being caught more, **predate** on cod, which leads to an increase in cod.
2	Spiny dogfish decreased, so cod in-creased.	Mentions spiny dogfish are significant without mentioning predation.
1	Spiny dogfish predate on cod.	Generic, truthful statement that doesn't have an argument or conclu-sion in it.
0	Because they don't hunt each other.	Something false, confusing, irrele-vant, etc.

6. i. What is the effect on **haddock?**

Answers	Score
Decreased a lot	3
Decreased a little	2
Stayed about the same	0
Increased a little	0
Increased a lot	0

ii. Why?

Score	Example	Description
3	Spiny dogfish, which are elasmobranchs, predate on cod. The decrease in elasmobranchs caused an increase in cod. Cod compete with haddock, so the increase in cod led to a decrease in haddock.	Mentions that spiny dogfish, which are being caught more, **predate** on cod, which leads to an increase in cod. Cod **compete** with haddock, so haddock decease.
2	There is more competition with cod due to there being less due to less spiny dogfish, which predate on cod.	Slightly less precise language or is missing some details, but mentions all of the key species involved.
1	There are more cod so there are less haddock.	Missing a lot of the details, mentions at least one of the relevant species.
0	Haddock populations decreased a little because spiny dogfish and skates compete with each other.	Something false, confusing, irrelevant, etc.

7. i. What is the effect on **windowpane?**

Answers	Score
Decreased a lot	3
Decreased a little	1
Stayed about the same	0
Increased a little	0
Increased a lot	0

ii. Why?

Score	Example	Description
3	Spiny dogfish, which are elasmobranchs, predate on cod. The decrease in elasmobranchs caused an increase in cod. Cod compete with haddock, so the increase in cod led to a decrease in haddock.	Mentions that spiny dogfish, which are being caught more, **predate** on cod, which leads to an increase in cod. Cod **compete** with windowpane, so windowpane decease. *OR* Mentions that winter flounder and yellowtail flounder both are **preyed** on by elasmobranchs. Since elasmobranchs decrease, yellowtail flounder and winter flounder increase. Both **compete** with windowpane, so windowpane suffers.
2	There is more competition with cod due to there being less due to less spiny dogfish, which predate on cod.	Slightly less precise language or is missing some details, but mentions all of the key species involved.
1	There are more cod so there are less windowpane.	Missing a lot of the details, mentions at least one of the relevant species but doesn't make a coherent argument.
0	There were no fish for them to eat.	Something false, confusing, irrelevant, etc. Mentions that the skates compete with windowpane.

Appendix C

IRB Human Subjects in Research

C.1 Evaluation Consent Form

CONSENT FORM FOR PARTICIPATION IN A RESEARCH STUDY

Visualizing Causes and Effects
A study carried out by Joel Wyatt for Dr. Colin Ware in the Data Visualization Research Lab at the University of New Hampshire.

What is the purpose of this study?
The purpose of this study is to find more effective ways of representing causes and effects both for understanding and explaining scientific data concepts. There will be approximately 100 participants.

Who may participate in this study?
You must be at least 18 years of age may participate.

What does your participation in this study involve?
In this study, you will be shown a visualization for an ecological fisheries model. You will be asked to explain the effects of different levels of fishing effort on various species. You will be trained for 5 minutes, followed by 8 to 10 minutes when you will be asked to make explanations. It will last less than 20 minutes overall.

What are the possible risks of participating in this study?
There are no known risks associated with this research.

What are the possible benefits of participating in this study?
The potential benefit of this research is that computer graphics data visualizations will be better designed in the future. At the completion of the study the results will be posted on the CCOM vislab web site.

Will you receive any compensation for participating in this study?
You will receive a packet of pens or a notebook for participating in this study.

Do you have to take part in this study?
Your consent to participate in this research is entirely voluntary. If you refuse to participate, then you will not experience any penalty or negative consequences.

Can you withdraw from this study?
If you consent to participate in this study, then you may refuse to answer any question and/or stop your participation in the study at any time without any penalty or negative consequences. You will still receive the compensation if you choose to withdraw from the study.

How will the confidentiality of your records be protected?
All data and records associated with your participation in this research will be confidential and only averaged data will be published. The data will be stored on a password protected computer and will only be accessed by principal investigator Colin Ware and graduate student Carmen St. Jean. There are, however, rare instances when the researchers are required to share personally-identifiable information (e.g., according to policy, contract, regulation). For example, in response to a complaint about the research, officials at the University of New Hampshire or the National Science Foundation may access research data.

Whom to contact if you have questions about this study?
If you have any questions pertaining to the research you can contact Colin Ware (862-1138, cware@ccom.unh.edu) to discuss them.

If you have questions about your rights as a research subject you can contact Dr. Julie Simpson in UNH Research Integrity Services, 603-862-2003 or Julie.simpson@unh.edu to discuss them.

I, _____ CONSENT/AGREE to participate in this research study

_____   _____
Signature of Subject   Date

C.2 Approval

<div align="center">

University *of* New Hampshire

Research Integrity Services, Service Building
51 College Road, Durham, NH 03824-3585
Fax: 603-862-3564

</div>

19-Jun-2013

Ware, Colin
Computer Science Dept
Ocean Engineering Bldg
Durham, NH 03824

IRB #: 4917
Study: NSF: Small: Interactive Causal Networks
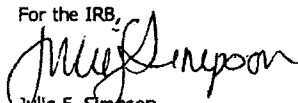**Review Level:** Expedited
Approval Expiration Date: 25-Jun-2014

The Institutional Review Board for the Protection of Human Subjects In Research (IRB) has reviewed and approved your request for time extension for this study. Approval for this study expires on the date indicated above. At the end of the approval period you will be asked to submit a report with regard to the involvement of human subjects. If your study is still active, you may apply for extension of IRB approval through this office.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the document, *Responsibilities of Directors of Research Studies Involving Human Subjects.* This document is available at http://unh.edu/research/irb-application-resources or from me.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or Julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

[signature]

Julie F. Simpson
Director

cc: File

C.3 Modification Approval

University *of* New Hampshire

Research Integrity Services, Service Building
51 College Road, Durham, NH 03824-3585
Fax: 603-862-3564

10-Mar-2014

Ware, Colin
Computer Science, Ocean Engineering Bldg
Durham, NH 03824

IRB #: 4917
Study: NSF: Small: Interactive Causal Networks
Approval Expiration Date: 25-Jun-2014
Modification Approval Date: 07-Mar-2014
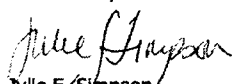**Modification:** Changes per 2/26/14 request

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved your modification to this study, as indicated above. Further changes in your study must be submitted to the IRB for review and approval prior to implementation.

Approval for this protocol expires on the date indicated above. At the end of the approval period you will be asked to submit a report with regard to the involvement of human subjects in this study. If your study is still active, you may request an extension of IRB approval.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the document, *Responsibilities of Directors of Research Studies Involving Human Subjects.* This document is available at http://unh.edu/research/irb-application-resources or from me.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or Julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

Julie F. Simpson
Director

cc: File