July, 2019

System Designs for Integrated Models of the Gulf of Mexico

Contents

Introduction

This report describes concepts for integrated models that answer stakeholder questions about oil spills in the Gulf of Mexico (GoM). The intent is to connect decision makers with tools that inform policy with the richest possible consideration of feedback, side effects, unintended consequences and counterintuitive behavior present in the broad system.

An integrated approach to GoM policy makes individual research efforts more valuable by placing them in context of related phenomena and linking them to user needs. It adds value for decision makers by providing better access to research, and thereby enabling better decisions.

Methods

The ideas in this report were elicited in a series of virtual workshops with researchers and board members from the Gulf of Mexico Research Initiative (GoMRI) in May and June, 2019. The workshops were designed to be much like the initial phase of a group model building session.[1]

Sessions & Format

In May, GoMRI led a series of four public webinars, focusing on human health, ecosystems, socioeconomics, and physics, an organization devised by GoMRI (Figure 1).

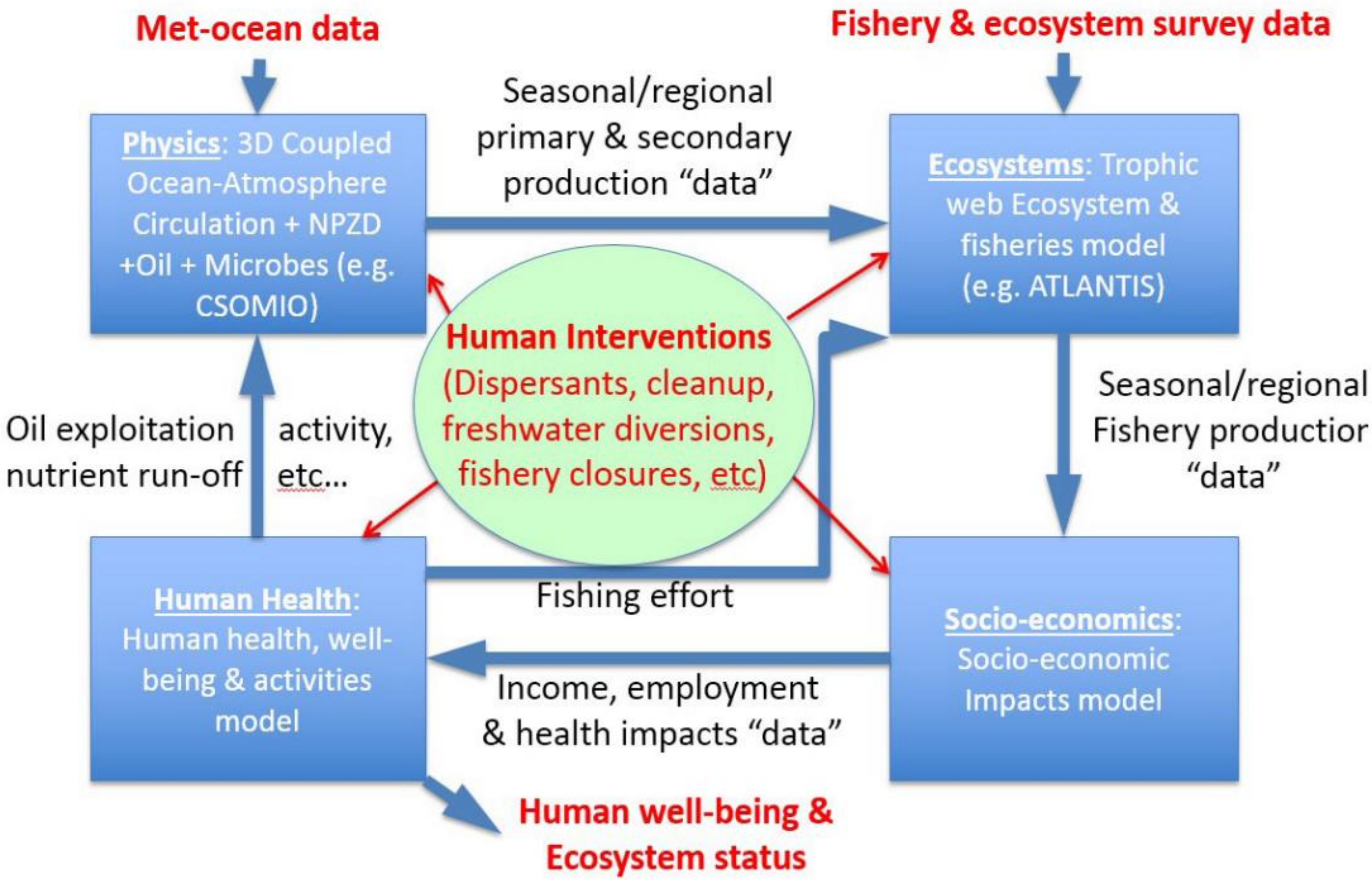

Figure 1: GoMRI Core Area 7B, Outline Integrated Model Structure (Courtesy of Dr. John Shepherd)

Each webinar was followed by an "A Session" workshop featuring (if possible) the speakers from the public webinar and other invited researchers. Each workshop began with some introductory framing questions, and then focused on collaborative construction and refinement of causal loop diagrams illustrating the key dynamics within and between the four sectors. Ventana facilitated the process and, after each session, updated the materials to consolidate comments and insights as a starting point for the subsequent session.

In June, a series of four "B Sessions" further refined the causal loop diagrams and other artifacts produced in the A Sessions. This provided an opportunity to connect with some researchers who were unavailable in the first round, and to explore a series of crosscutting issues more deeply. The first two B Sessions focused on Physics & Ecosystems and Socioeconomics & Health, because those emerged from the A sessions as natural pairings. The final B Sessions considered the system as an integrated whole.

Framing Questions

A key phase in model development is scoping, i.e. determining what questions will be answered by the model and therefore what time horizon, boundary, detail and dynamics it must include. At the start of each session, we reminded participants of these design questions.

<u>Design Questions</u>

- Audience
  - Who are the decision makers?
  - What other stakeholders are involved?
- Theory of change
  - Whose behavior will change?
  - How will the model bring that change about?
- Scope
  - Questions will be answered?
  - On what time horizon?
  - With what detail?
- Logistics
  - How is data collected and shared?
  - Who runs and maintains the model?
  - How are results disseminated?
- Who runs it
  - Updates it
  - Collects data
  - Tracks performance
- How does the modeling community grow together?

<u>Stakeholder Questions</u>

In order to establish model requirements, the webinars made frequent reference to stakeholder questions collected by SeaGrant.[2] Since there are many, we used a force-based network layout from kumu.io to visualize the structure of the questions.[3] In one rendition, Ventana assigned topic tags to each question, and colored questions according to the 4-box structure (Figure 1). One can see that the 4-box structure is somewhat natural, in that questions self-organize into a similar scheme (Figure 2), with ocean physics (blue) interacting with socioeconomics (orange) mediated by ecosystems (yellow) and health (green).

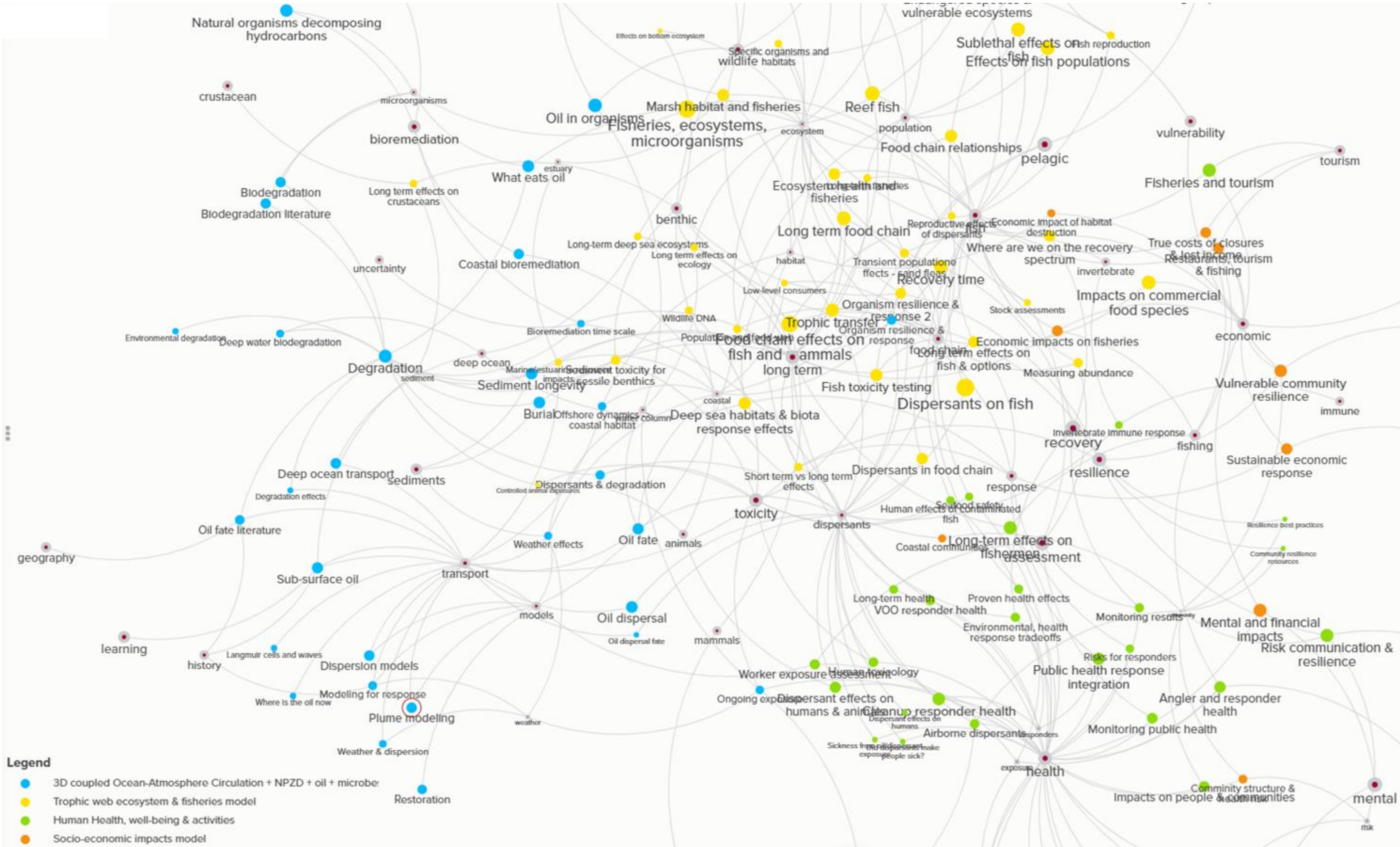

Figure 2: SeaGrant question topic network.

Similarly, we used VOSviewer to construct visualizations of the text network in stakeholder questions and the titles of research in the GoMRI portfolio.[4,5]

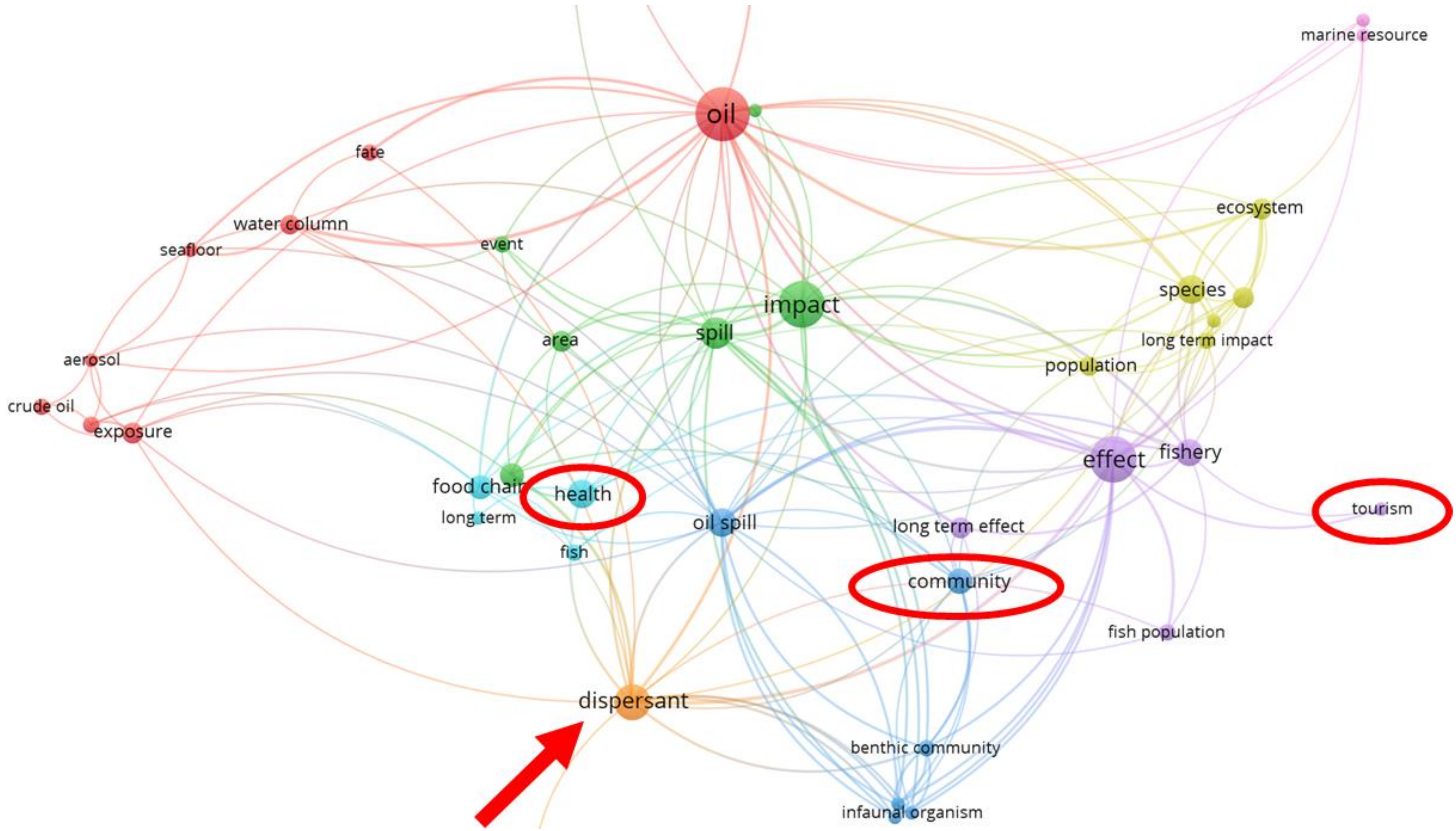

Figure 3: Term network for SeaGrant questions, showing the importance of dispersants (arrow) and socioeconomic impacts (health, community, tourism, circled).

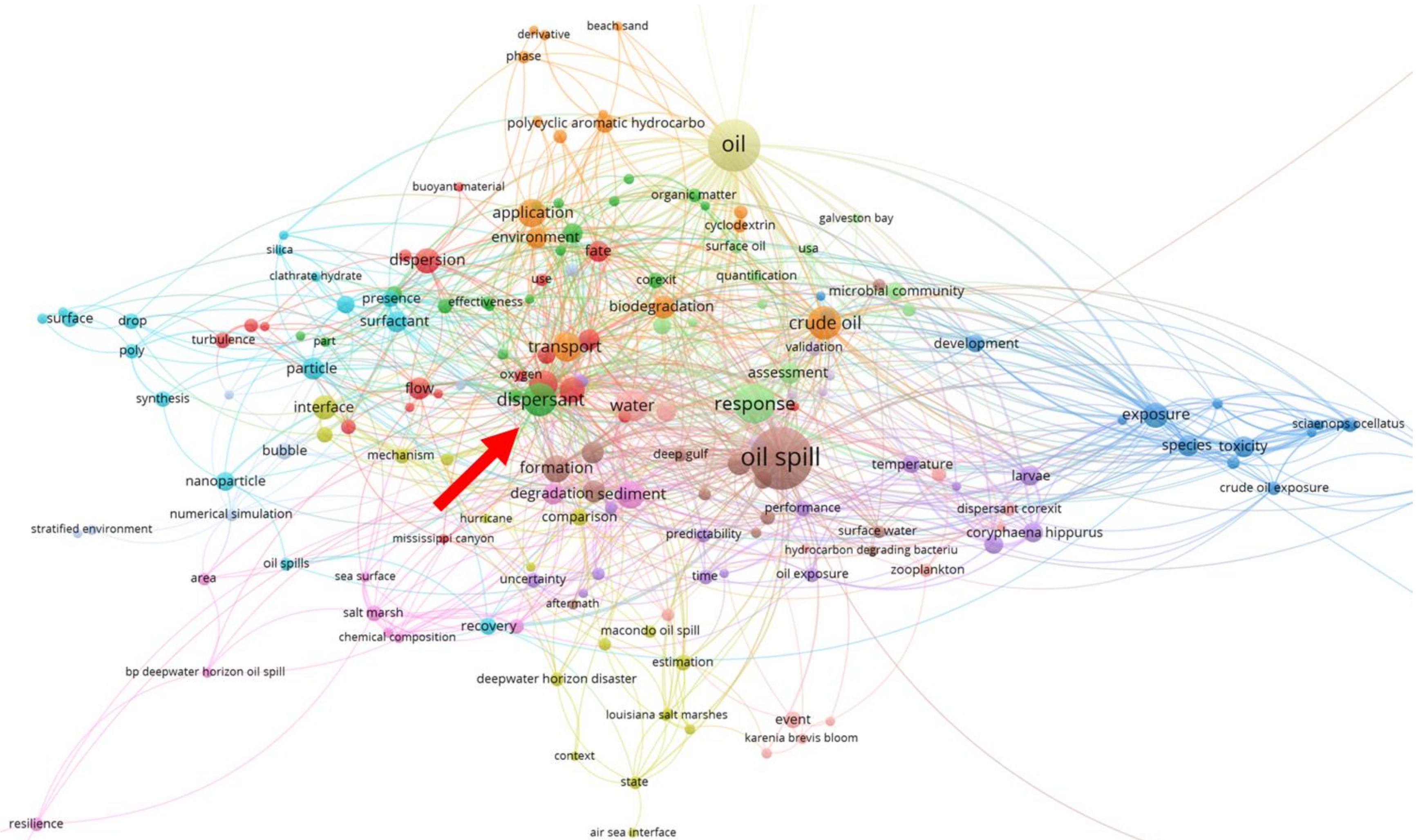

Figure 4: Term network for GoMRI research article titles, indicating the centrality of dispersants, but also notably few socioeconomic concepts.

Other Artifacts

To elicit comments that might reveal interesting dynamics, we asked about the temporal evolution of phenomena in the Gulf. Normally, in a group model building session we would ask specifically about the "reference modes" of a number of state variables, but time was limited in our sessions, so we elected to ask the question in a general way.[6] We used a figure from Navrud et al. as a starting point, and marked it up with participant comments.[7]

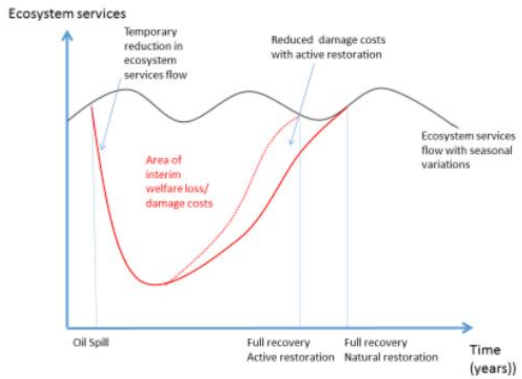

Figure 1. Temporal flow of marine and coastal ecosystem services (ES), and the service loss/damages due to an oil spill; with and without active restoration of the services.

Figure 5: Starting point for reference mode discussion.

The result was illuminating. Participants amended the chart (Figure 6) to note that:

1. The initial state for a spill in the GoM is already depressed from the cumulative effects of past degradation events.
2. Some measures can be taken to prepare the system, so that the response to a spill is mitigated in advance.
3. Some restoration measures that improve the long run response can make things worse in the short run (e.g., cleanup disturbing the shoreline).
4. There may be irreversible long-term effects (akin to the previous effects leading to the depressed initial state in #1).
5. A useful aspiration is to "bounce forward," i.e. to find synergies among policies that lead not only to restoration of the immediate effects of a spill, but to improvement of the long term health of the system.

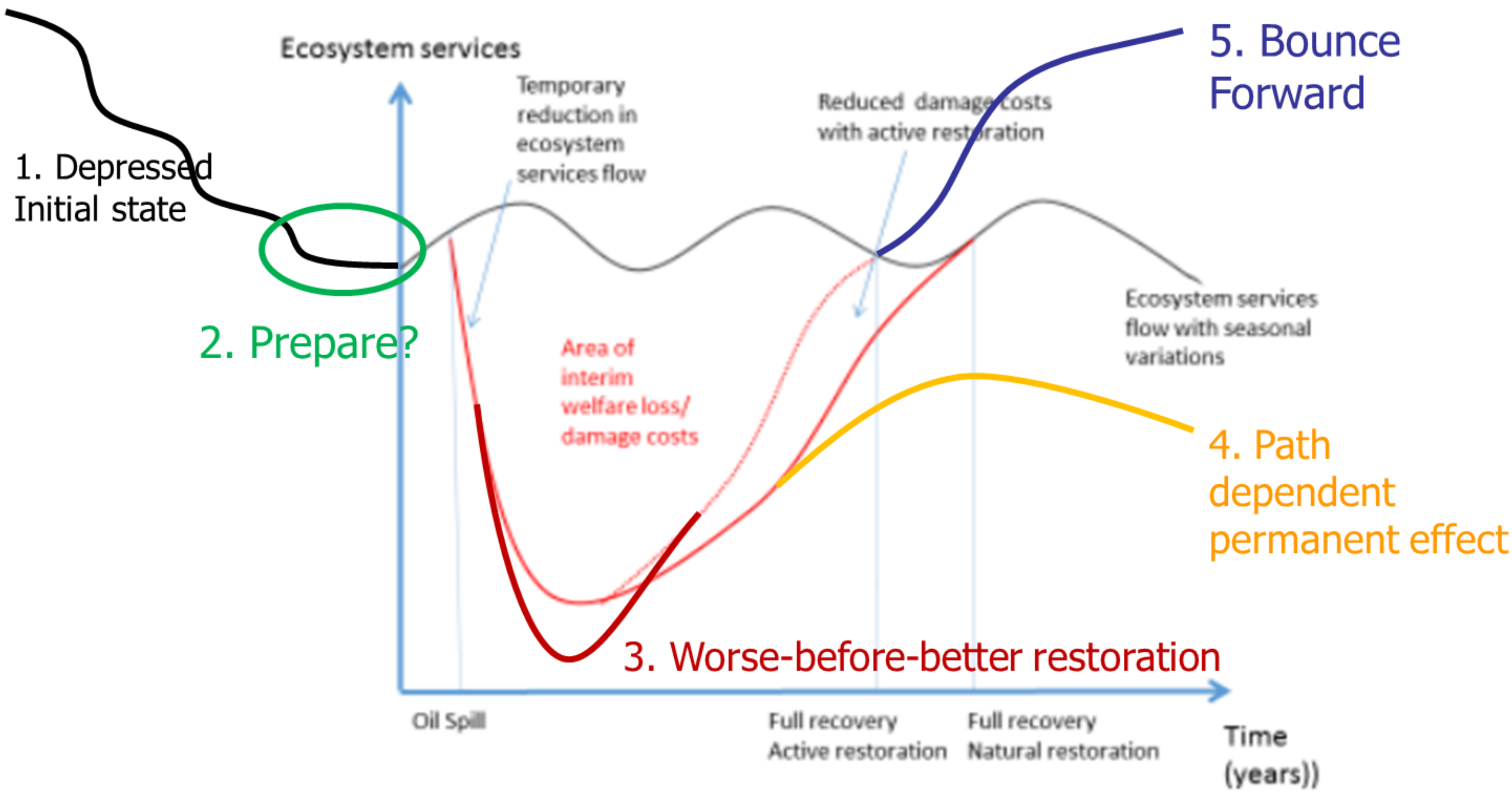

Figure 6: Marked-up temporal evolution of GoM impacts.

Evolution

The central focus of our efforts was the creation of diagrams documenting the GoM system, which could be the conceptual foundation for integrated models. We began with the 4-box concept (Figure 1) and elaborated the structure live during each webinar, using Vensim® as a whiteboard.[8] In the first A Session on Human Health, the diagram was extremely crude (Figure 7). However, the session yielded extensive verbal comments, which were used to produce an updated diagram with many more features as a starting point for the second A Session.

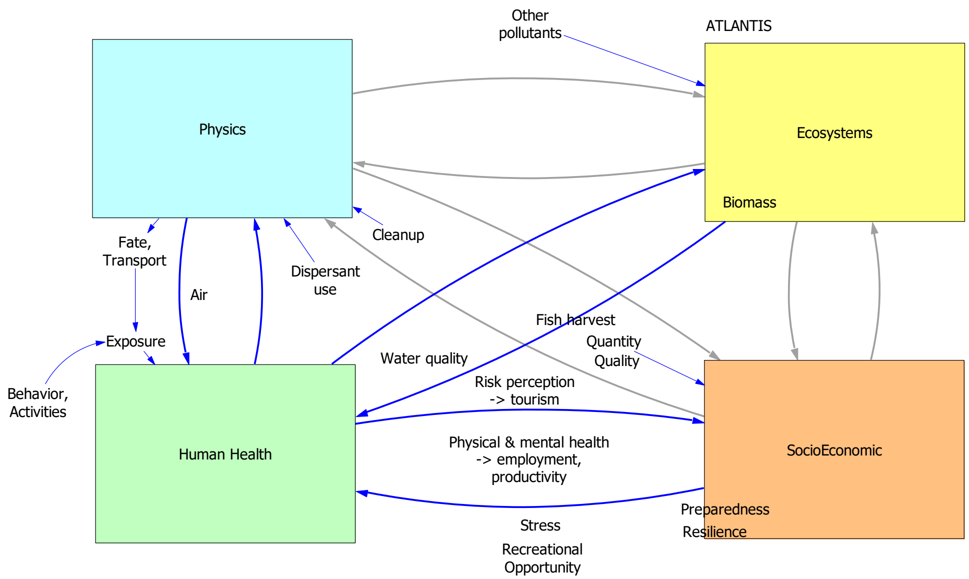

Figure 7: Marked-up diagram after first A Session.

After five more iterations, we arrived at a final system diagram, incorporating many more relationships (Figure 8). It can only be considered "final" in the sense that it will not be further elaborated within the scope of the current project. The model could always be revised and expanded to improve its fidelity and utility.[9]

Often, the additional structure identified in a session did not reflect the nominal disciplinary boundary of the session. For example, in the Physics A session, much of the conversation considered other topics, including ecosystems and perceptions (Figure 12). We consider this a feature of the approach, not a bug. It is indicative of the breadth of expertise and interests among the researchers involved and the intrinsic connectivity of problems.

A causal loop diagram (CLD) is, as the name implies, a depiction of the causal mechanisms that lead to change over time in a system. Each label on the diagram represents a variable that can increase or decrease, and each arrow indicates influence of the source variable on the target. Frequently, a CLD includes arrowhead markings (+, -) indicating the polarity of each connection, and icons indicating the polarity of feedback loops in the model. We chose to omit these features in most instances, because our purpose was to establish conceptual linkages among domains rather than to immediately simulate the system. In any case, the number of feedback loops would be too large to permit delineation of loop polarities without further segmentation into multiple diagrams.

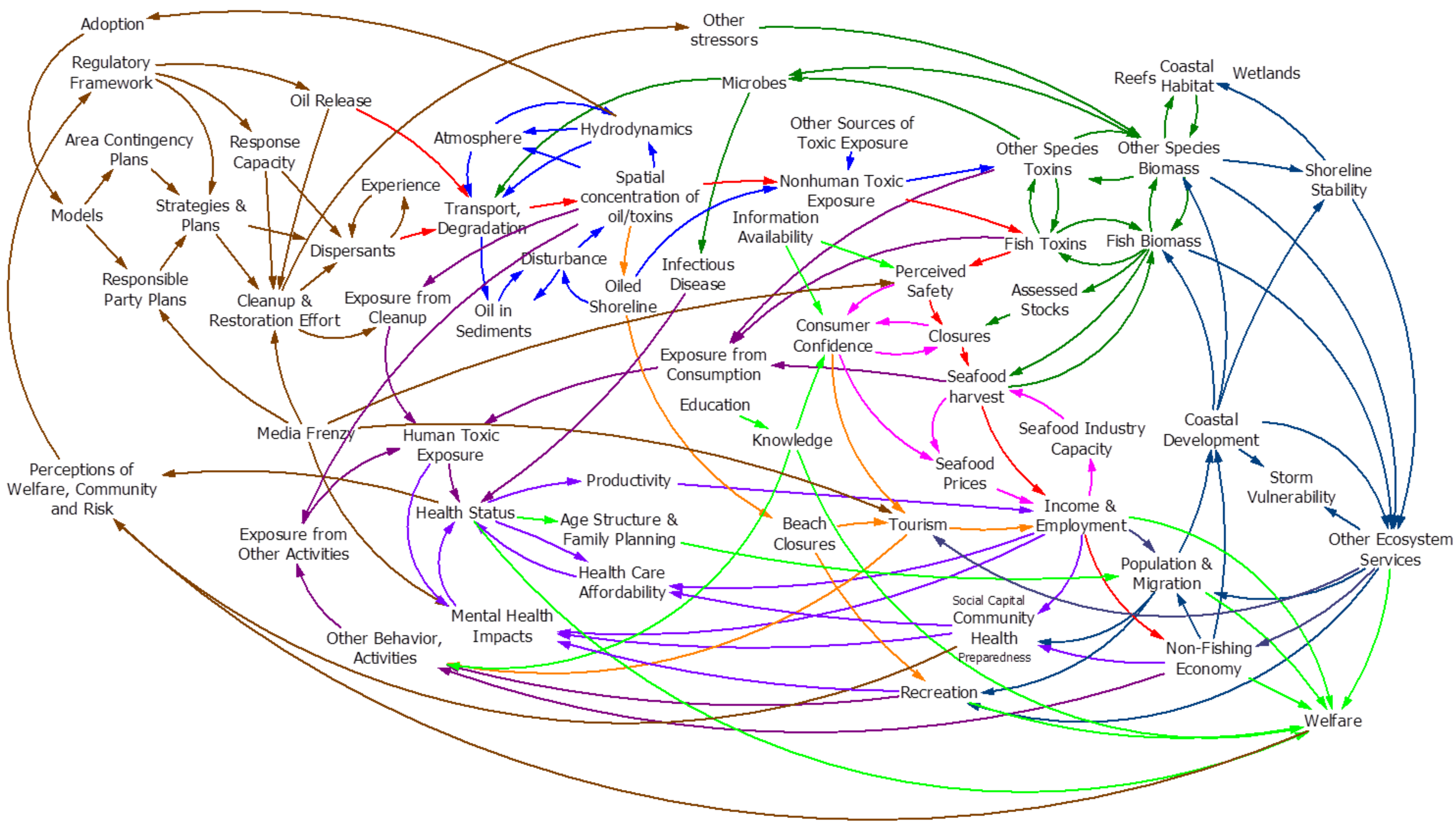

Figure 8: Final System Causal Loop Diagram. The system still somewhat preserves the 4-box structure, with physics at upper left (blue cluster), ecosystems at right (green), socioeconomics at bottom right, and human health at lower left (purple). However, the boundaries among domains are not always well-defined.

Key Features of the System

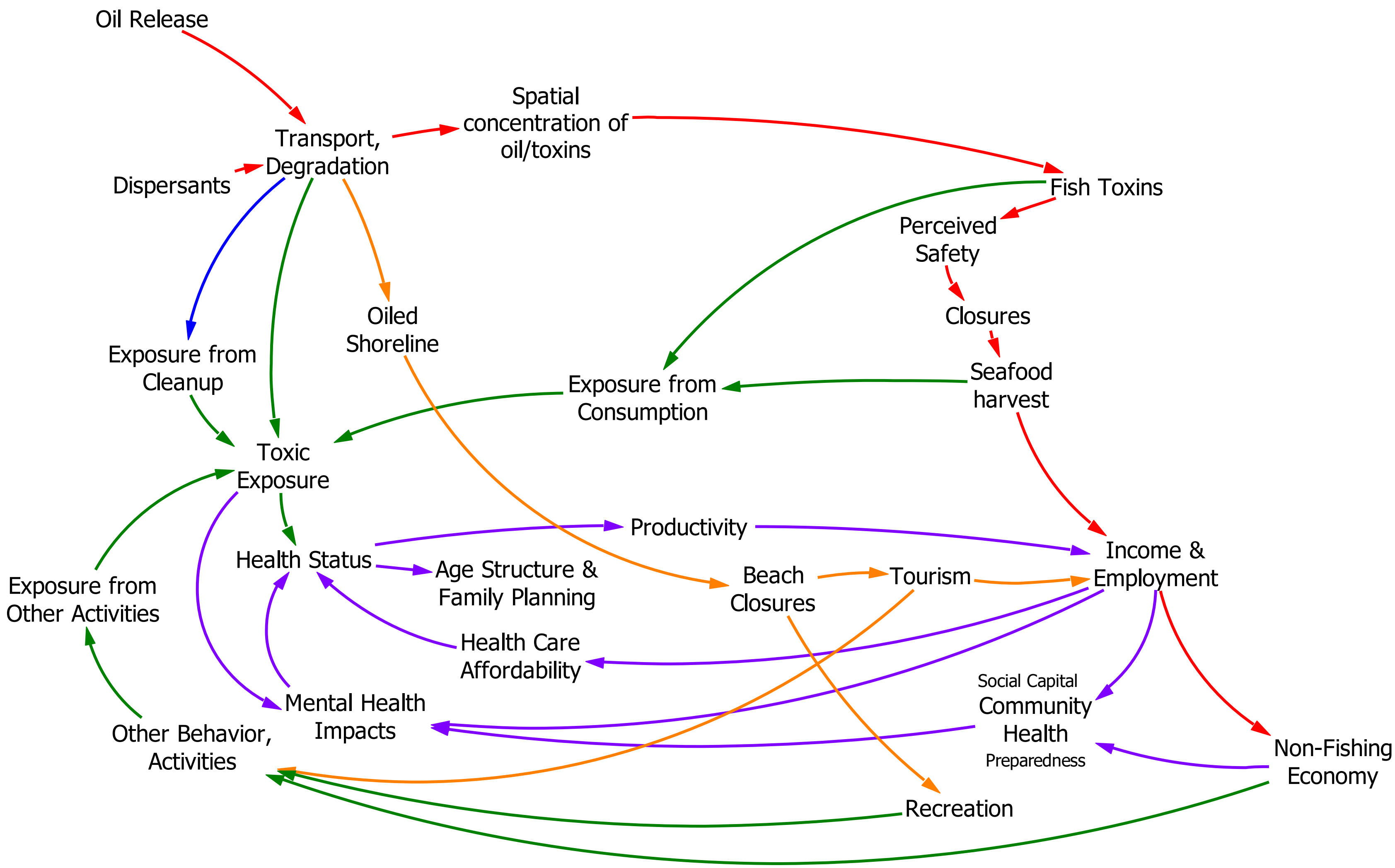

Figure 9: Features of the system after the Human Health A Session. Red: the chain of events from a spill, impacting fish toxicity, leading to fisheries closures, with repercussions for income and employment (largely inspired by a study with the CMS model). Green: human health risk from toxic exposure, through cleanup, seafood consumption, recreation and other pathways (largely inspired by the BEACHES model). Purple: feedback loops that couple income and employment, community health, mental and physical health, and productivity.

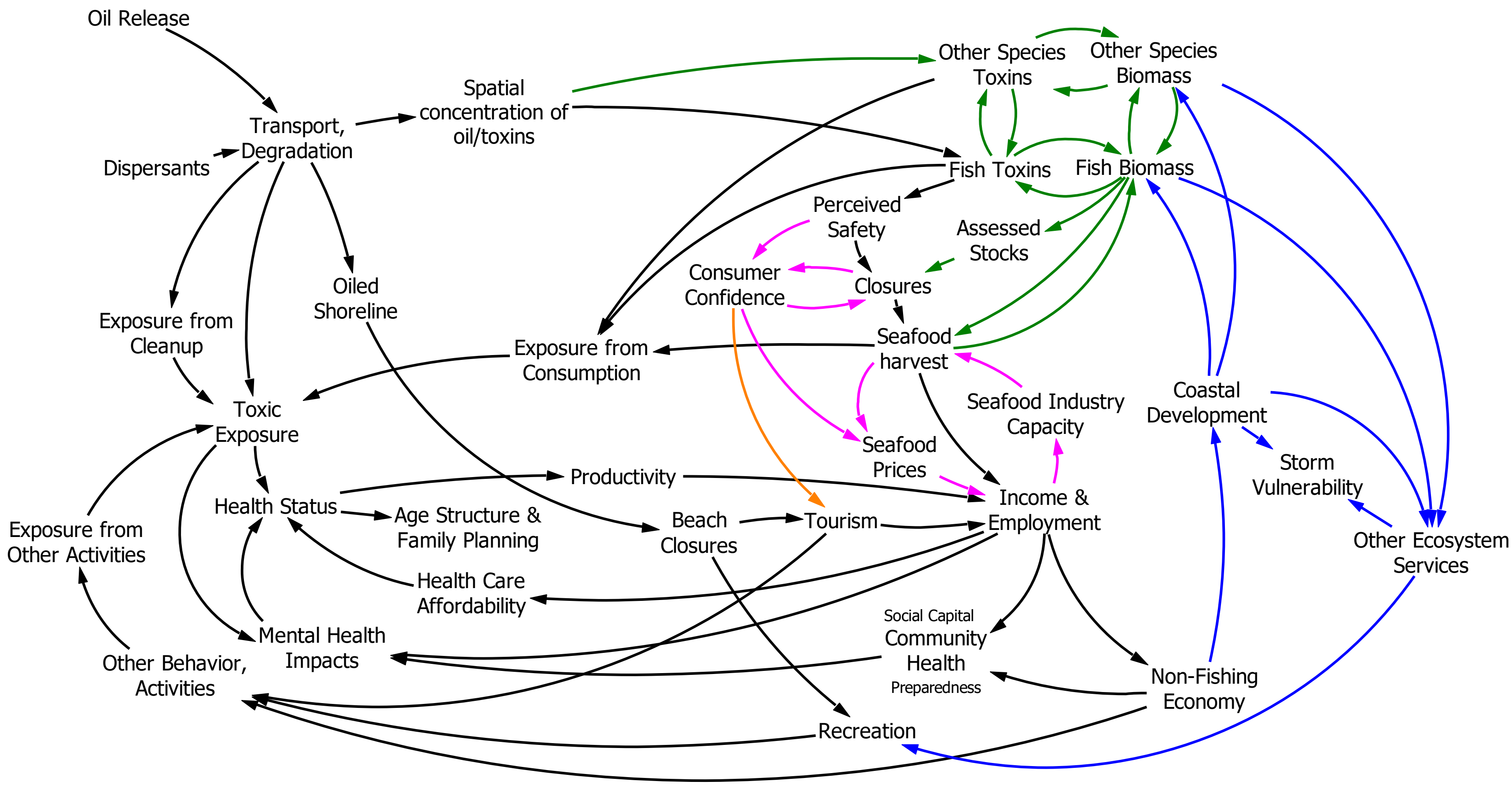

Figure 10: Some additional features after the Ecosystems A Session. Green: expanded ecosystem with biomass of fish and other species and feedbacks from fish stocks to closures and harvest. Pink: effect of consumer safety perceptions on closures and seafood prices (plus tourism in orange), and seafood industry price and capacity feedbacks. Blue: ecosystem service value and interactions between coastal development and ecosystems (implicitly, particularly habitat).

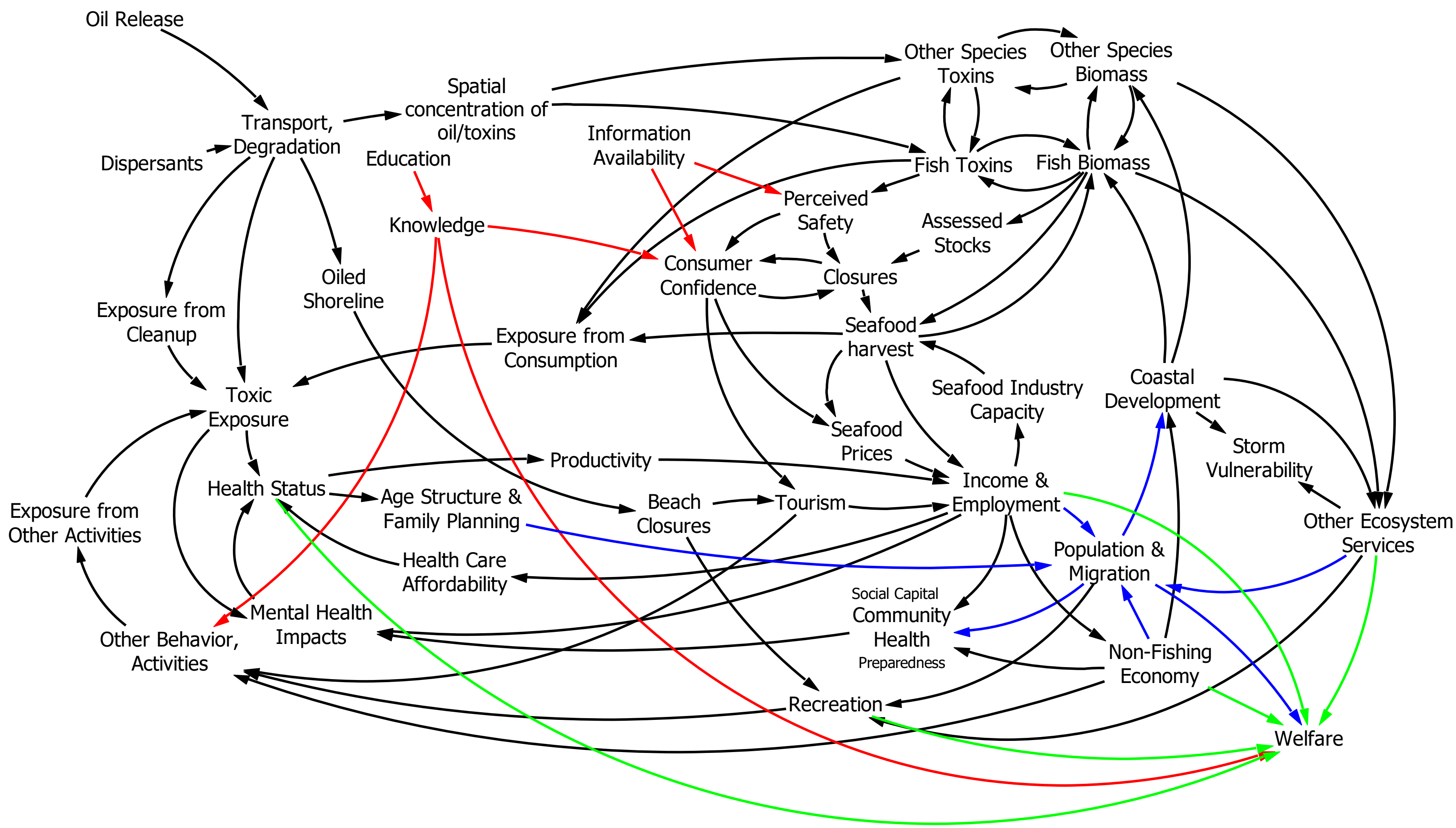

Figure 11: Additional features after the Socioeconomics A Session. Green: human welfare drivers. Blue: population and migration, driven by attractiveness of the coastal environment from employment, ecosystem and health considerations. Red: the importance of knowledge and information availability as modifiers of behavior and intrinsic components of welfare.

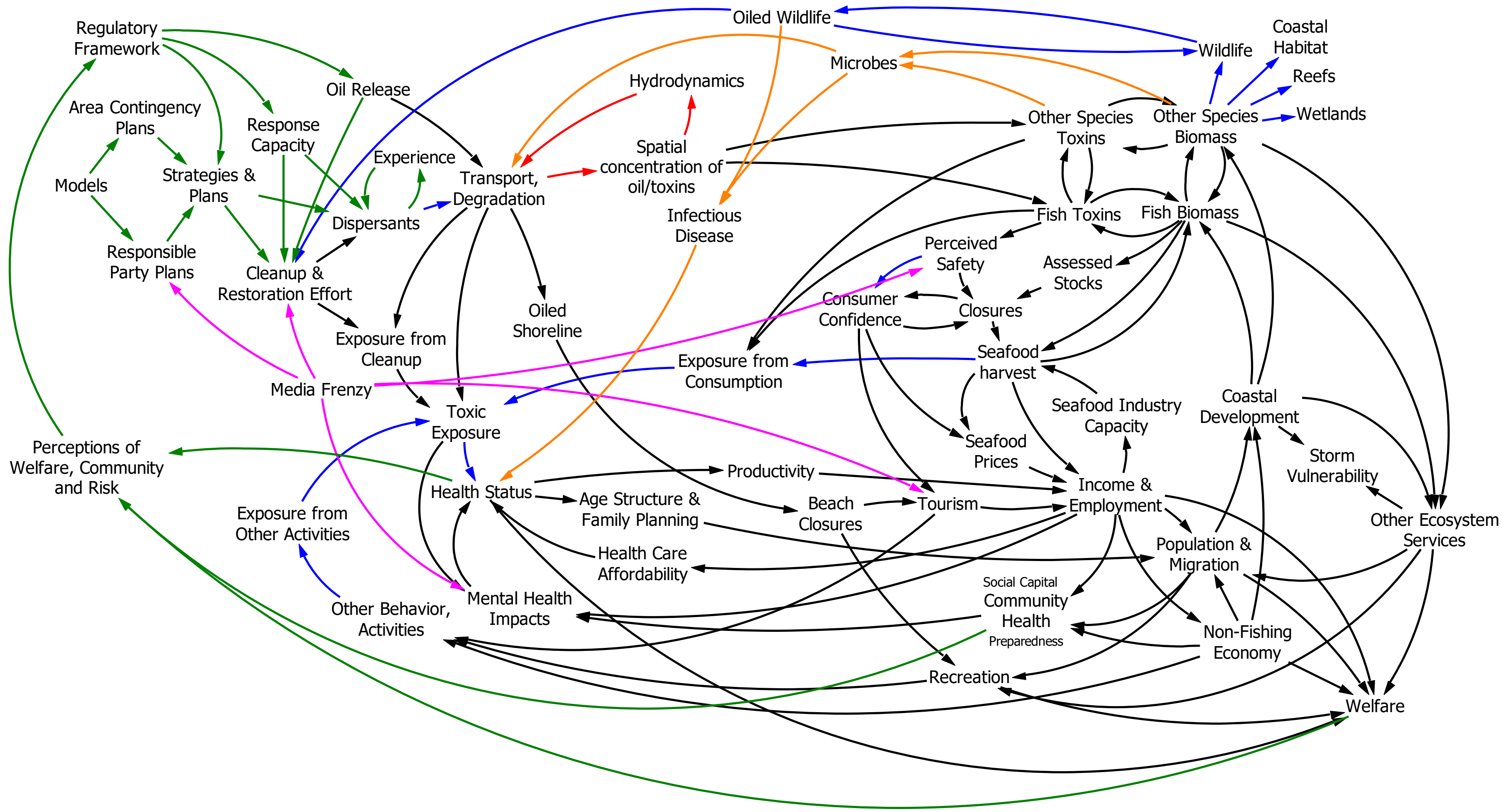

Figure 12: Additional features after the Physics A Session. Red: oil-hydrodynamic interactions (not shown, but discussed: ocean-atmosphere interactions). Orange: the role of ecosystems, particularly microbes, in transport and degradation and as disease vectors. Blue: the role of wildlife as foci of restoration efforts, and placeholders for particular ecosystem features, like reefs, that should be elaborated. Pink: media frenzy influencing public perceptions, behavior and health (but lacking causal drivers). Green: features of the operational modeling domain, including models used to guide response efforts and experience effects that can cause "lock-in" to particular strategies (here, dispersants).

Mapping of Models to the Structure

As we mapped the structure of the system, we took note of the extent to which existing models cover the system, or could be linked to do so in the future. Participant comments identified a number of knowledge gaps and opportunities (Figure 13). In a related effort, we mapped model boundaries onto the CLD and identified links that were present or absent in existing models (Figure 14).

We discuss the gaps and opportunities with respect to integrated modeling further in Design Directions below. However, a number of items were also mentioned that are "local" to a particular box in the model. These include:

Physics

- Better exploitation of coupled ocean-atmosphere modeling
- Dynamic effects of oil – 2 phase flow
- Scenario repositories for downstream use

Ecosystems

- Mobile species behavior
- Dose-response for toxins

Health

- Dose-response & observational health
- Mental health risk
- Health delivery capacity and economic impacts

Socioeconomics

- Regional economy - spillovers from direct impacts
- Community growth, education, equity, health, climate
- Decision making

Generally, the human systems (health & socioeconomics) were perceived as much less developed.

Figure 13: Participant suggestions for additional models and knowledge gaps.

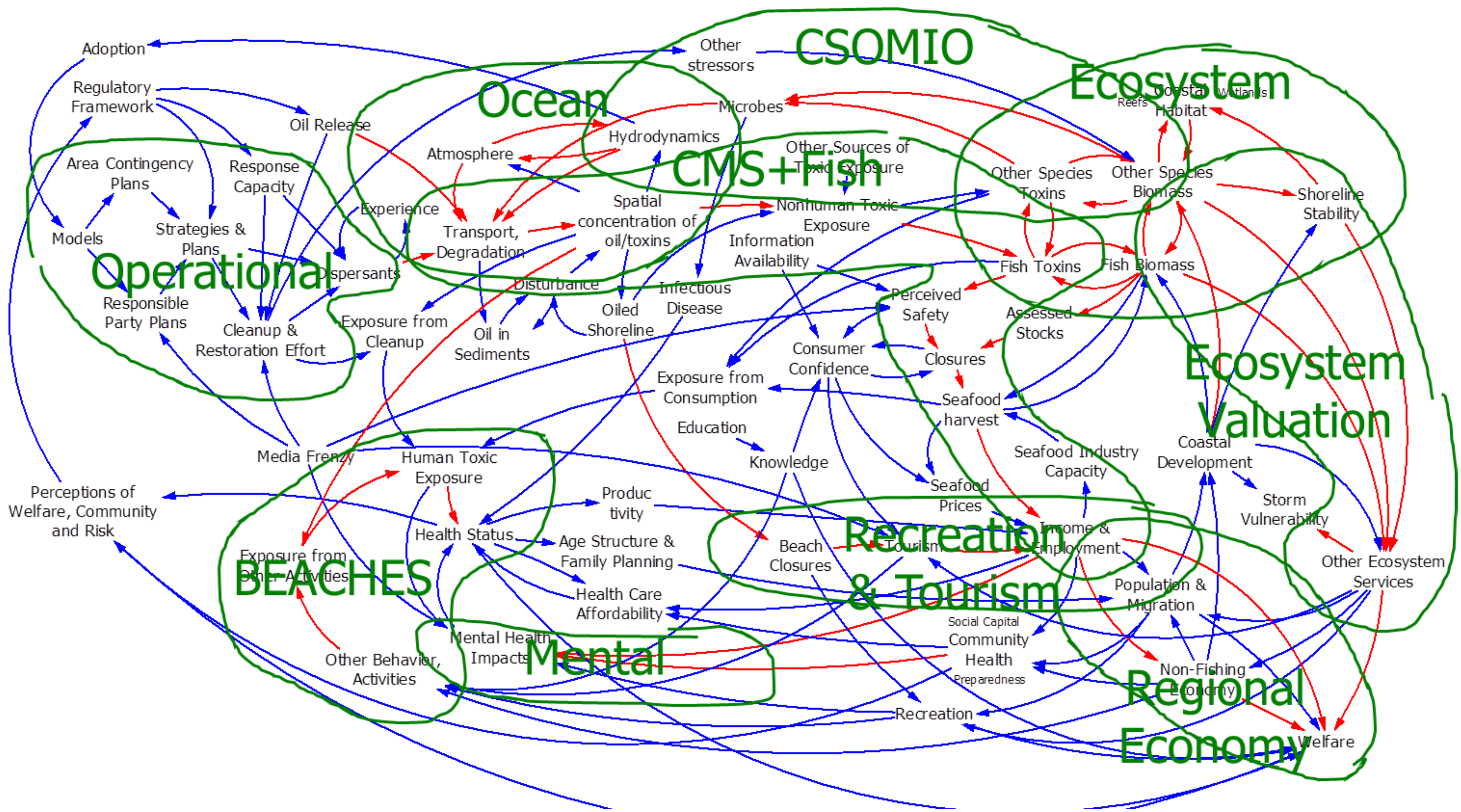

Figure 14: Existing model domains, overlaid on the system causal loop diagram. Green annotations indicate the rough boundaries of models identified in the workshops. Red links are present in one or more models. Blue links have not been included in integrated models.

Augmented 4-box Structure

The original 4-box conceptual structure proved extremely fruitful throughout the process. However, after the operational domain surfaced in the Physics A discussion (Figure 12), we realized that the initial conception of the socioeconomic box was not comprehensive. Figure 15 augments the 4-box structure with domains of governance, industry activity, technology, and spill response. This brings the control loops that govern the occurrence of and response to oil spills into the framework. This occurs on two time scales. In the long run, goals and perceptions in the human system drive investments and changes in technological options. One might also include the evolution of the financial system and its view of coastal economies for purposes like insurance and lending as part of this long term evolution. In the short run, industry activity (drilling, safety investments) and spill responses occur in context of the institutions, regulations and technologies that developed in the long run.

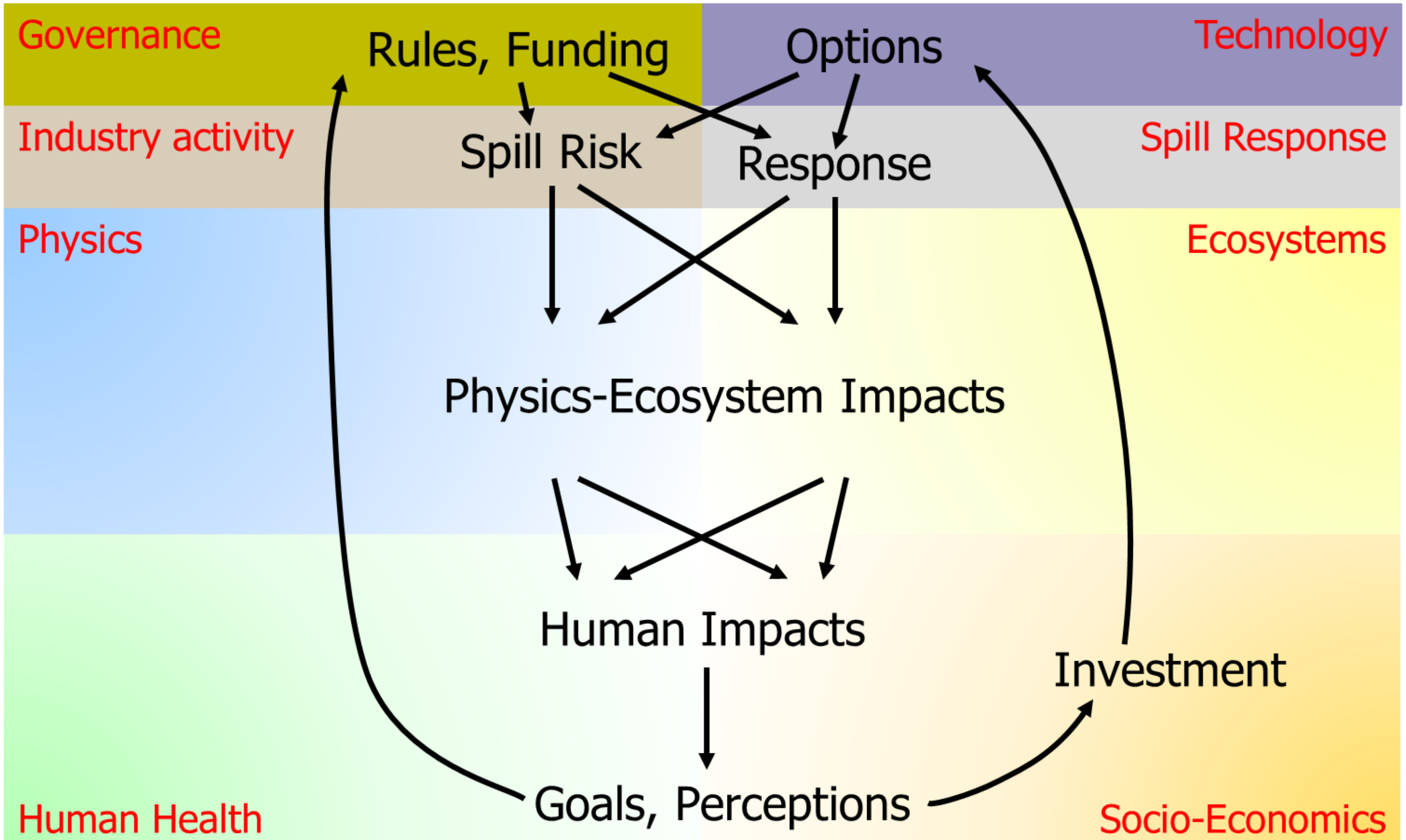

Figure 15: Augmented 4-Box Structure.

Design Directions

At a high level, several strategies for science-stakeholder integration emerged during the workshops.

- Increasing access to existing research.
- Closing knowledge gaps in local problem domains in order to better span the Gulf system.
- Making existing research into reusable components.
- Supporting federation of model components more deliberately.
- Creating top-down, strategic models of the entire GoM system.

We discuss each approach below.

What is the question?

Much of the GoMRI research portfolio answers questions that are narrowly scientific, within a particular domain. This is crucial, because the science is constructing models of how things work, and without that understanding it is difficult to advance policy discussions.

		Stakeholders, Decision Makers					
		Int'l < Fed	State	Local	Indiv	Corp	NGO
Questions, Decisions	Spill response	EPA (civil, criminal)		SeaGrant network		DWH trustees	
	Safety regs	CDC, NOAA, FDA, EPA	Health dep, beach adv.	->"			
	Leasing						
	Coastal development		Master Planning				
	Community health	FDA	Advisories	->"			
	GDP, Jobs						
	Networks						
	Institutions						
	Resilience	(FEMA) NOAA + 25 – task force, OPA90	Formal engagement framework	->		Responsible Party	
	Technology			Tech Xfer outreach			

Table 1: Stakeholder questions and decisions.

At several points during the workshops, we attempted to map stakeholders and questions to particular decision points in the system. Table 1 is the result of one approach. No clear leverage point emerged from these efforts. However, it may be possible to shorten the path between policy and science, increasing the value of research, by connecting researchers to decision making needs more directly. We think that explicit efforts to share existing knowledge of stakeholder needs more widely among researchers, and to create situations in which decision makers and researchers interact, could go a long way to strengthening the connections between science and policy. One could think of this as a deliberate augmentation of the existing social networks that disseminate information about the Gulf (Figure 16).

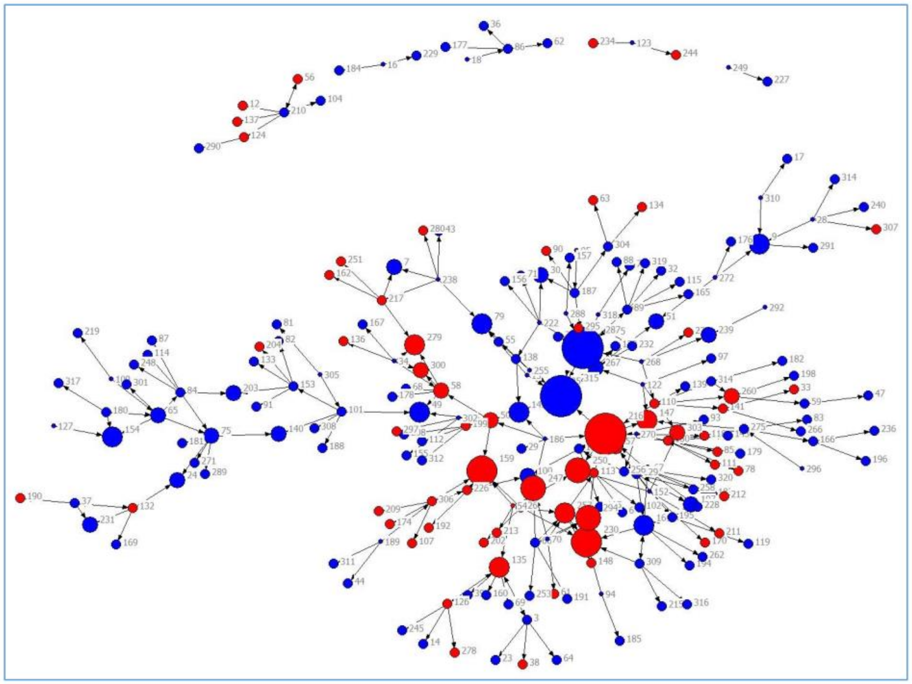

Figure 2. Indegree centrality of GoMRI-funded scientists (red nodes) that were present in the SNA. (Blue nodes indicate not a GoMRI-funded scientist.)

Figure 16: SeaGrant Social Netwok Analysis.[10]

Integrated Modeling Strategies

The briefing materials for several workshops included the table of approaches to model integration in Table 2. This provides a useful organization for discussion of options.

Table 2: Integrated modeling strategies.

Approach	**Portfolio** Coordinate a family of independent models that each tackle a subset of the problem.	**Federation** Combine multiple large-scale models through APIs or data flow, simulating in a chain or iterating to equilibrium.	**Megamodel** Create a single, detailed model integrating all aspects of multiple domain models.	**Metamodel** Create a single, top-down model containing response surfaces or other simple representations of detailed components.
Pros	Leverages existing tools	Leverages existing tools Preserves detail	Integrated *and* detailed	Highly integrated, fast
Cons	Not truly integrated	Difficult to manage interfaces	Extremely resource intensive	Aggregation

Portfolio

Obviously there is already an extensive portfolio of GoM research and models. Without literally connecting these models, more could be done to access the components in a connected way. For example, the GoMRI publications page could be enhanced from a hierarchical list to an overlapping topical tag structure that would give users more entry points. In particular, socioeconomics, and member concepts like resilience, could be added to the list of themes.

Going further, the research page could be the basis for an interactive portal or guide to research (along the lines of a wiki, the IPCC assessments, or the SEDAC Thematic Guide to Integrated Assessment, for example).[11] One example for the Gulf is the Gulf Spill Restoration site maintained by NOAA for the DWH Trustees.[12] The damage assessment integrates a wide variety of topics (Figure 17), including links to datasets. However, it is also somewhat limited in that it serves only a single decision-making event, and lacks a number of feedbacks that were identified in this work.

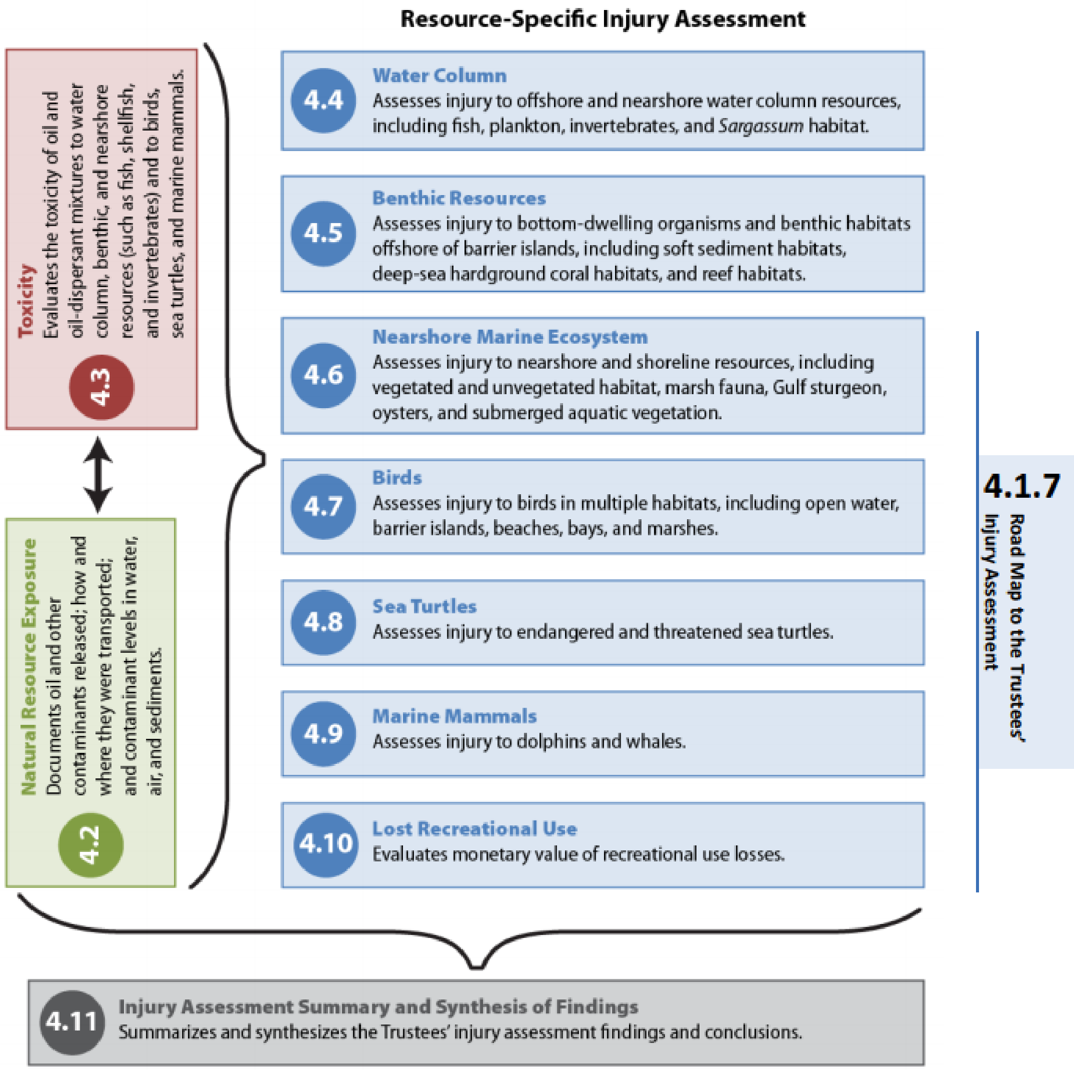

Figure 4.1-7. "Road map" to the Trustees' injury assessment presented in Chapter 4.

Figure 17: Gulf Spill Restoration road map.

Federation

Integrated models considered in the webinars already contain a high degree of integration, particularly among the physics and ecosystems boxes.

There appear to be two qualitatively different federation strategies at work. One is the use of chained models to capture causality from the physics of oil in the ocean, through ecosystems, to socioeconomic impacts. Figure 18 shows one such example that emerged in the workshops, inspired by the CMS (but probably not depicting that work precisely).[13]

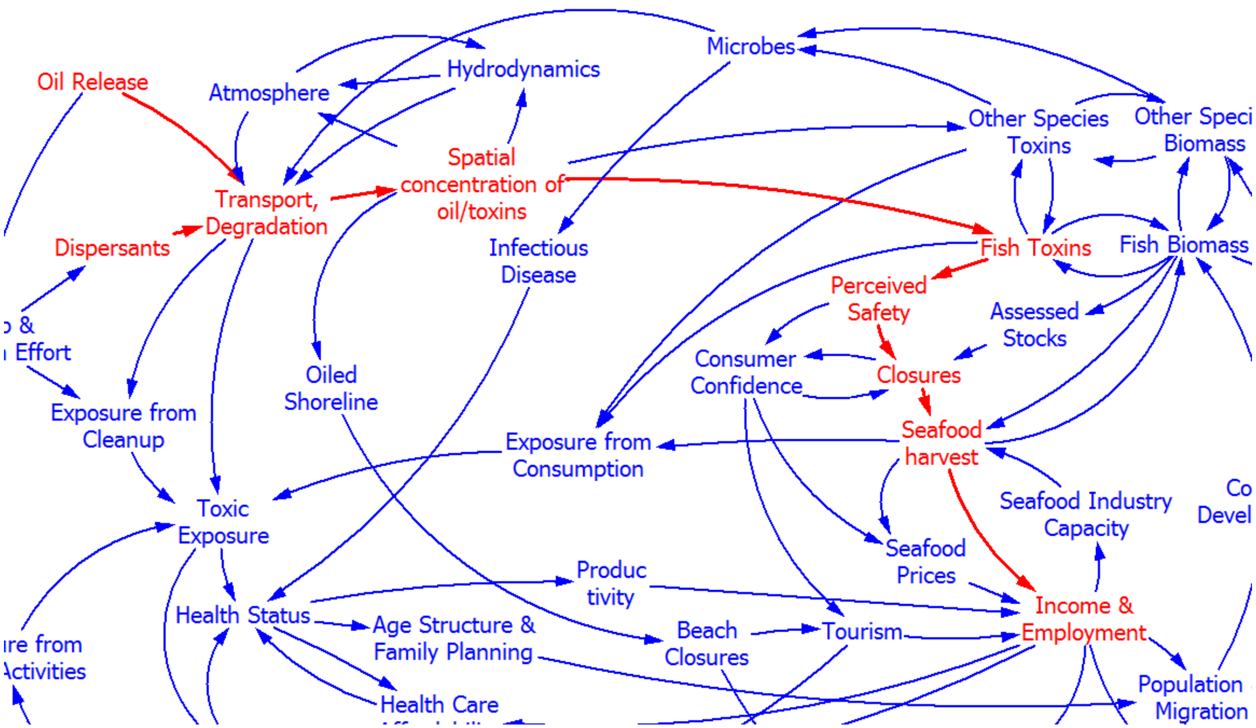

Figure 18: Integrated representation of an impact pathway via chained models.

The chaining strategy works because the GoM system contains some natural components with tightly-coupled internal interactions (Figure 19) and limited feeback between subsystems.

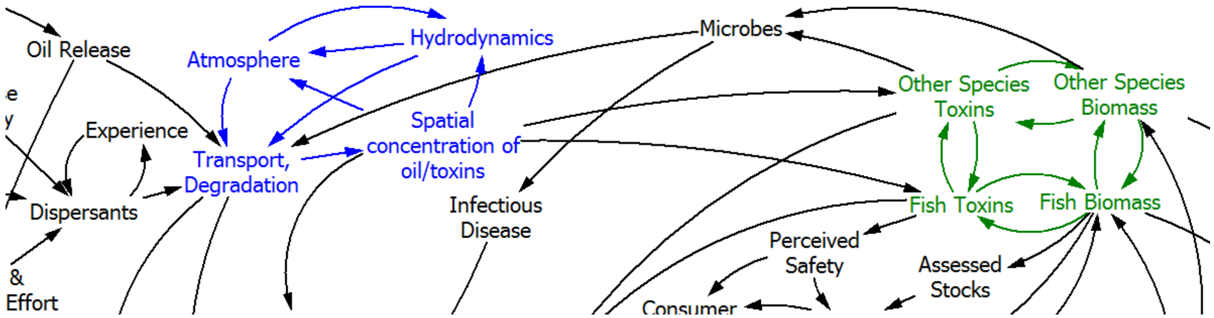

Figure 19: Feedback clusters in physics and ecosystems.

Where the assumption of compartmentalized feedback must be relaxed, as in the investigation of the evolutionary impacts of toxins on microbial evolution and the ecosystem's role in transport and degradation (Figure 20), other strategies may be needed. While existing models can sometimes be federated with feedback through an API, this is often cumbersome, requiring a new dedicated model.

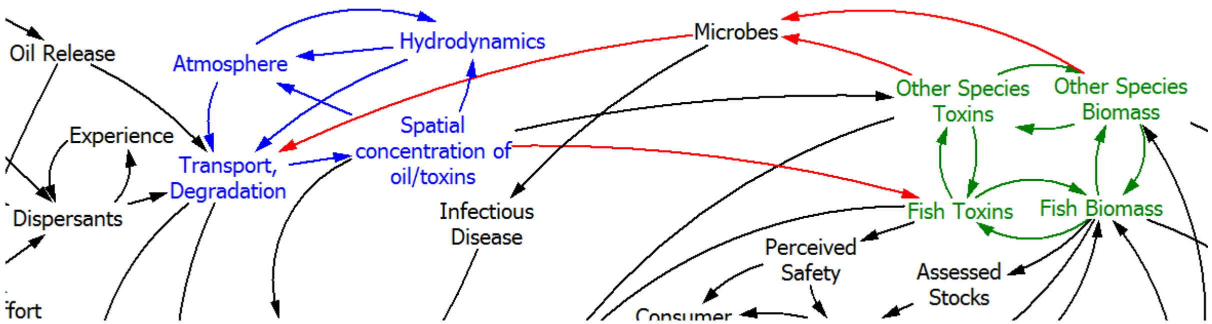

Figure 20: Example of ecosystem-physics feedback.

Feedback is especially challenging at the intersection of socioeconomics and human health (Figure 21). Economic factors have strong effects on health, and health and perceptions of health have strong effects on economics. Some social concepts like community resilience have no clear boundary between the two subsystems. The challenges are particularly great in these areas because much of the foundational research needed to construct integrated models is in its infancy.

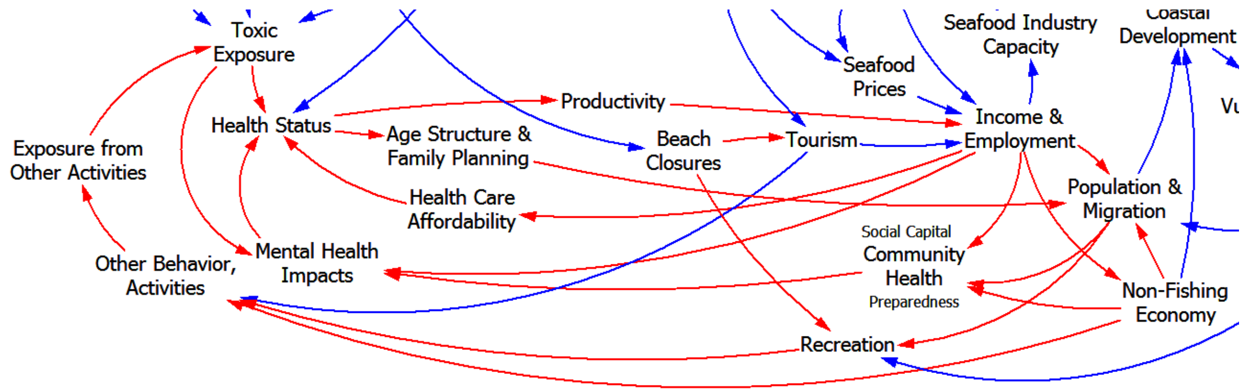

Figure 21: Tight coupling between socioeconomics and health.

While different strategies are needed for different domains, several opportunities emerged in the workshop discussions.

Scenario Repositories

As participants noted, there are several examples of infrastructure for federating models in climate science and policy that could be emulated for the GoM. The Coupled Model Intercomparison Project (CMIP) is essentially a product of atmosphere-ocean physics, but its product is a library of spatially-detailed climate scenarios that have proved extremely useful in other contexts, including a wide variety of socioeconomic models.[14] CMIP outputs, along with observational data, are available in public repositories like the KNMI Climate Explorer.[15,16] Complementary repositories for the RCPs and SSPs provide socioeconomic emissions drivers for climate models.[17,18]

Reusable Economic Models

Many impacts of a spill share a common generic structure, in that the direct effects on a resource are amplified by spillovers into the general economy. Christa Court presented one such example in the May public webinars (Figure 22).[19] It is common to use models like REMI and IMPLAN to assess the economic multiplier effects in similar cases.[20] There is an opportunity for making this component of impact assessment more available and reusable, so that future researchers do not need to reinvent it. This might also be an easy way to bring economists into GoM research.

Economic models typically omit a number of resources with important implications for the long term evolution of communities, including concepts like resilience that are of clear interest to Gulf stakeholders. For example, in an input-output framework, education and health care activities do not actually produce health, happiness or productivity as outputs. Therefore a complementary model of some of the off-market phenomena in coastal communities would be a desirable reusable component for future integration of spill impacts on human systems. A rough concept is shown in Figure 23.

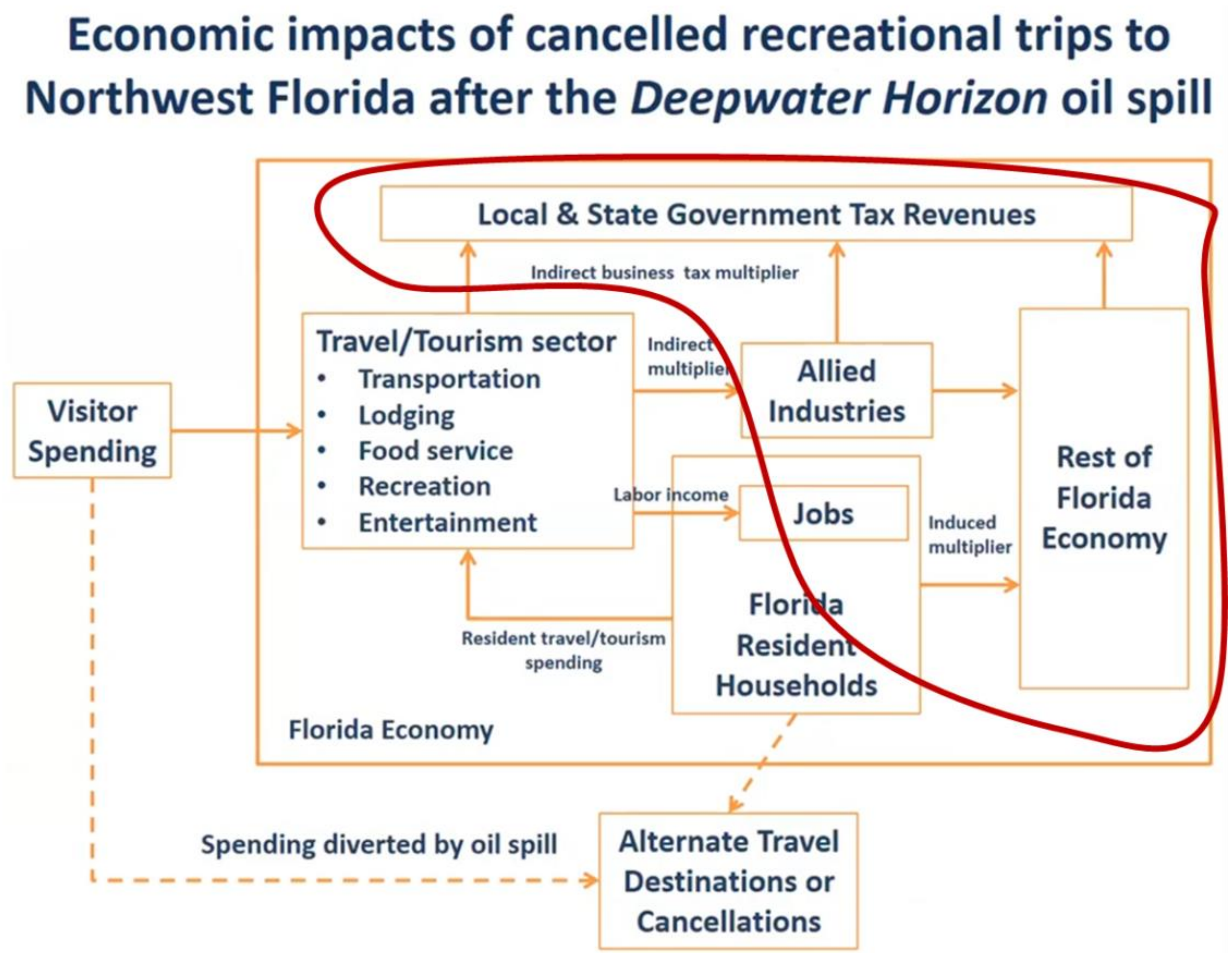

Figure 22: Economic components in a model of tourism impacts. Generic, potentially reusable component indicated in red boundary.

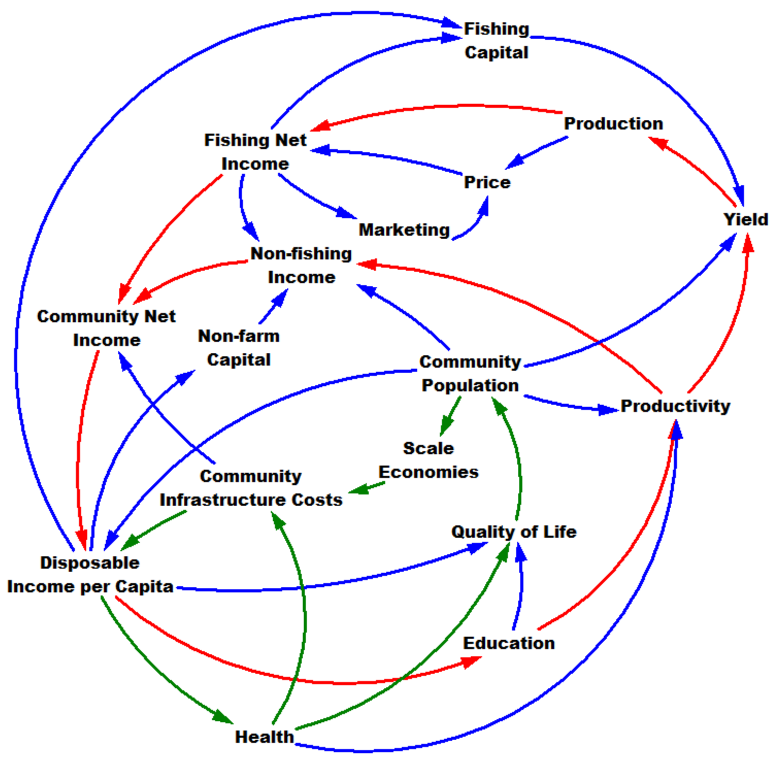

Figure 23: Some long term community dynamics.

Scaling Health Models

The BEACHES model described in the May health webinar also constitutes a potentially scalable generic structure.[21] By expanding the vector of activities, target populations and diseases considered, similar approaches could easily integrate a larger domain. Such an approach would also benefit from access to reusable inputs, as described above in Scenario Repositories.

Megamodels & Metamodels

In climate science, atmosphere-ocean models have evolved into earth system models and are developing into highly-integrated human-earth models.[22] These efforts are extremely resource intensive, and it remains impractical to implement most facets of socioeconomic systems in spatial, physical models. This approach seems premature for the Gulf.

Sandifer et al. describe a conceptual Disaster-Pressure-State-Ecosystem Service-Response-Health (DPSERH) model.

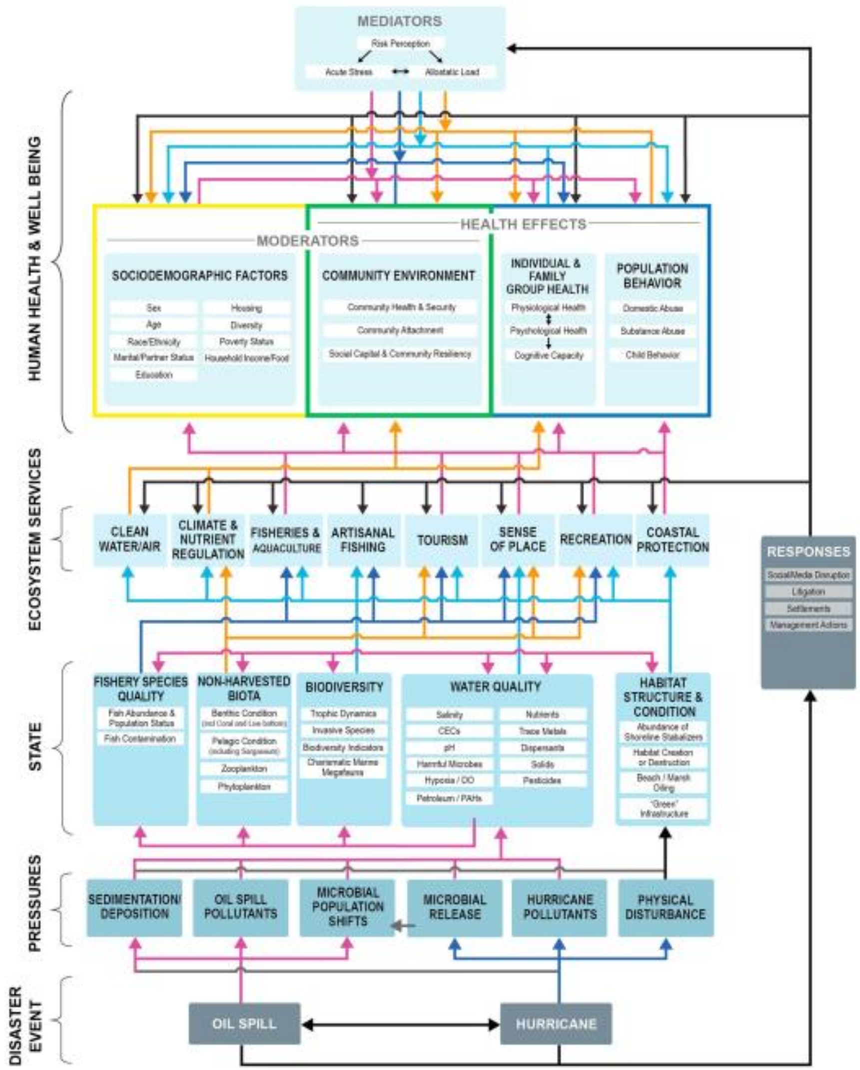

Figure 4. The overall DPSERH model, showing connections among various components. These connections are not meant to be all inclusive but rather illustrative. All arrows shown are based on existing literature or data. Different colors used for arrows have no significance other than to increase ease of following specific connections among model elements.

Figure 24: Integrated model concept from Sandifer et al.

Since the Sandifer et al. model is conceptual, it is underspecified relative to a simulatable implementation of the same scope. However, it is a useful road map for integration that highlights multiple features that are missing from the current model portfolio. It may be possible to implement subsets of the concept via federation of existing model components. Constructing the model de novo, one would have the advantage of choosing a practical level of detail for each concept.

Sandifer et al. rightly identify the importance of capturing broad feedbacks for valuing oil spill impacts and guiding response efforts. Their specification is a bottom-up response to the problem. We believe there is also a complementary top-down modeling approach that explores physics-ecosystem-human feedbacks in a general, strategic way, described in the next section, A Minimal Integrated Model.

Community Development

The evolution toward more integrated models must include the community of modelers. We believe there are substantial opportunities for cross-fertilization among the various communities – modelers and non-modelers, scientists and decision makers – that could enhance the relevance and speed the development of integrated tools.

A Minimal Integrated Model

While it was beyond the scope of the project to create a runnable model, Ventana elected to do so, because it might generate useful thinking. Technically, we aimed for a model that would be:

- Fast, for interactive exploration
- Transparent, with results traceable to assumptions and decisions
- Robust
- Capable of embracing uncertainty
- Connected to economic and social side effects
- Calibrated to data
- Simple, minimizing detail complexity in favor of breadth and dynamics

In addition, we felt that the model should include a few key, qualitative features of the GoM system that emerged during elicitation of the CLDs:

- One or a few state variables for each of the 4 boxes.
- At least one major link between each pair of boxes, especially in the underrepresented health and socioeconomic domains.
- A tradeoff between mitigating oil surfacing with dispersants and toxicity.
- Irreversibilities in ecosystem-habitat interactions, such that permanent damage might occur.
- Tension in coastal economies between losses from closures and gains from cleanup activity.
- Delayed health effects.
- A closed loop between socioeconomics (the community-economy) and health, through mental health impacts and productivity.

At a high level, the feedback among subsystems is shown in Figure 25.

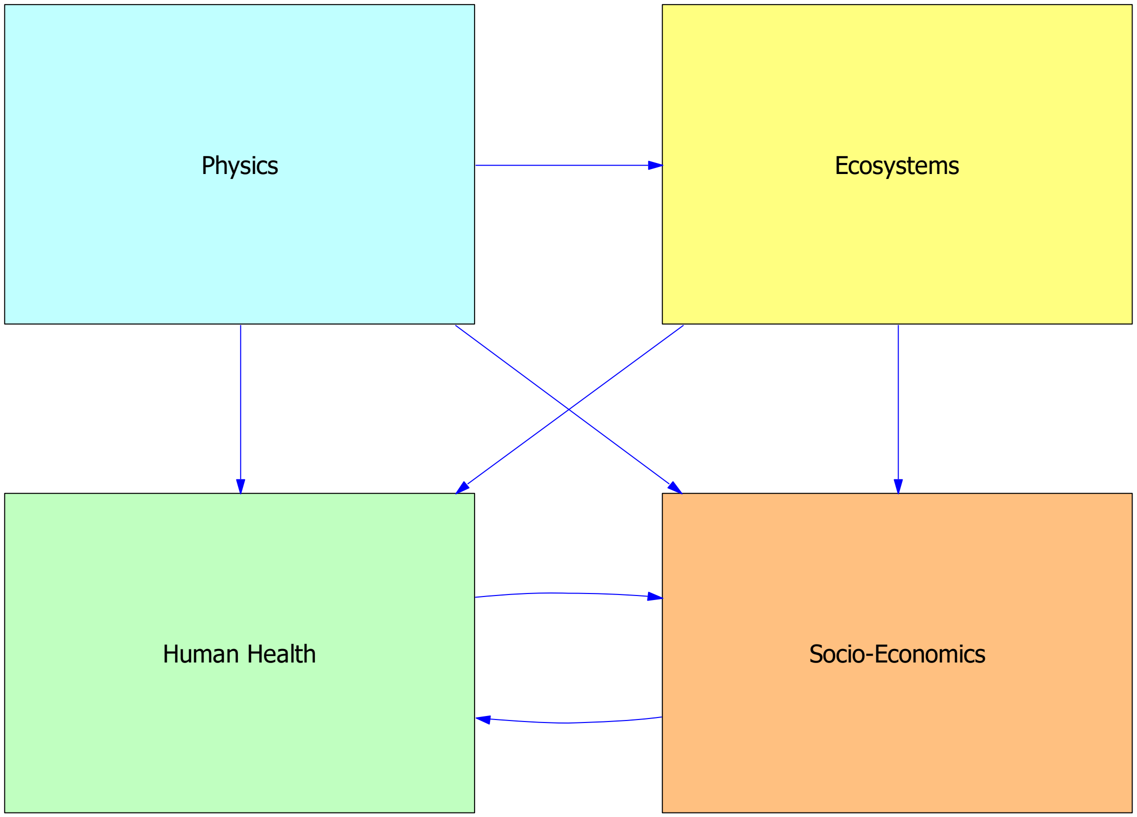

Figure 25: High level feedback among subsystems in the Meta-GoMRI model.

The model is implemented in Vensim using System Dynamics methodology. That is to say, it is a system of ODEs representing physical variables as well as behavioral decision making. It is extremely simple overall, with 11 state variables and just over 150 equations and parameters in total. It runs on an abstract 20-year time horizon, and is notionally parameterized to resemble the Deepwater Horizon spill in scale. Most variables are indexed in relative or arbitrary terms rather than calibrated to actual GoM values.

Physics

The physics sector contains an aggregate ocean with dispersion of toxins via diffusion processes with first-order dynamics at each point (Figure 26). It is driven by exogenous release of oil (at bottom). It has no inputs from other sectors, and therefore ecosystem dynamics influencing oil transport are not captured, for example. Three policies are available: surface oil cleanup (e.g., skimming), deployment of booms to slow transport of oil onshore, and cleanup of beached oil. Each of these creates a negative feedback loop at the top of the diagram.

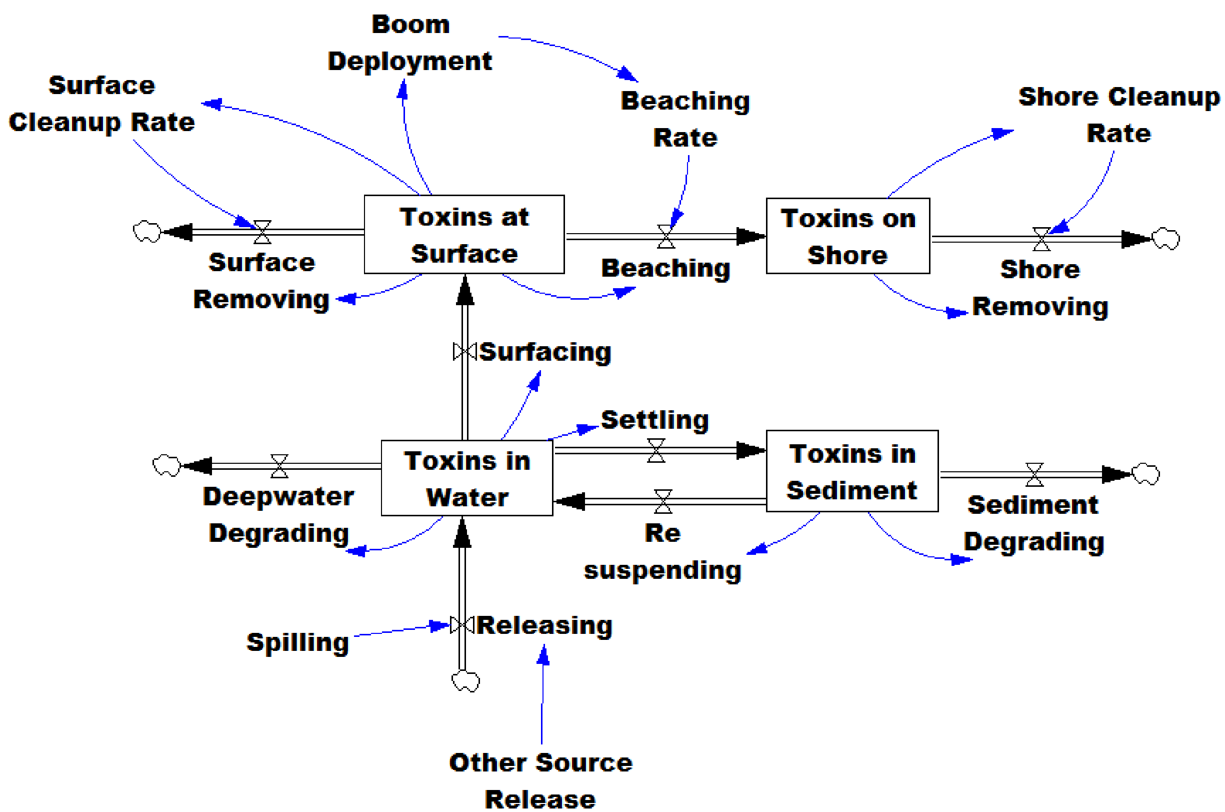

Figure 26: Physics subsystem.

Each policy is represented by an extremely simple behavioral decision rule. For example, boom deployment is a nonlinear function of the observed presence of toxins (i.e. oil) on the surface (Figure 27). While in reality there would be implementation delays and constraints on deployment due to the availability of equipment, these are neglected. The thresholds for action on each policy implicitly reflect economic and health considerations from other sectors.

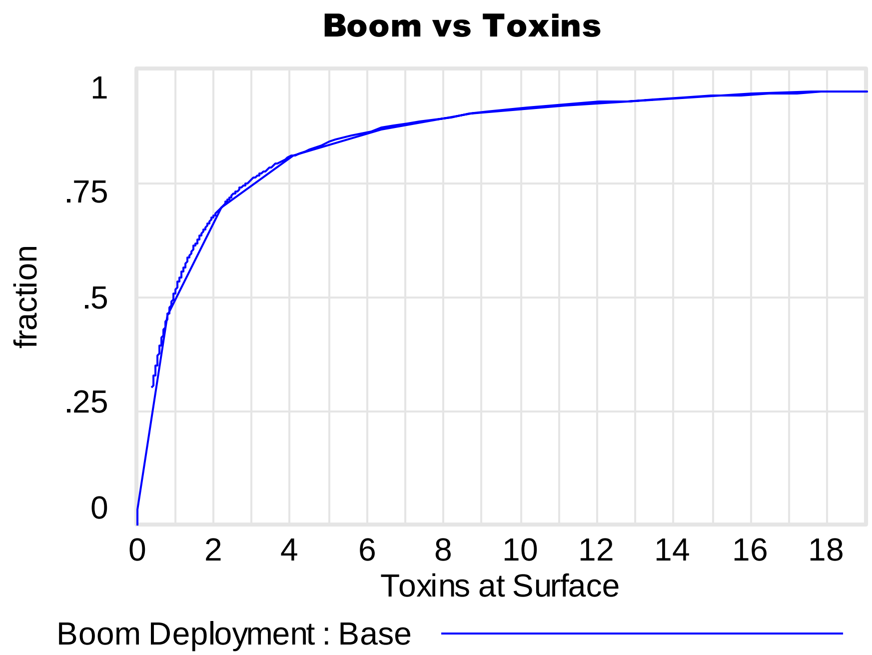

Figure 27: Boom Deployment as a function of Toxins in Surface Water.

Ecosystems

The ecosystem sector contains two states: biomass and habitat. Biomass health is influenced by mortality from toxicity, which is a weighted average of the presence of toxins (i.e. oil and dispersants) in the 4 states of the physics sector. Habitat is influenced by disturbance from shore cleanup, e.g., adverse sedimentation from excavations. The stable habitat depends on the quantity of biomass (as, for example, shorelines depend on seagrass for stability) and in turn the biomass carrying capacity depends on the extent of habitat (as fish require healthy reefs).

Aggregation of the ecosystem into two states is obviously heroic to the point of absurdity, but the structure does represent a few important features of the real system. Because it is nonlinear and path dependent, a temporary disturbance can have a sustained negative impact on biomass and habitat (Figure 29).

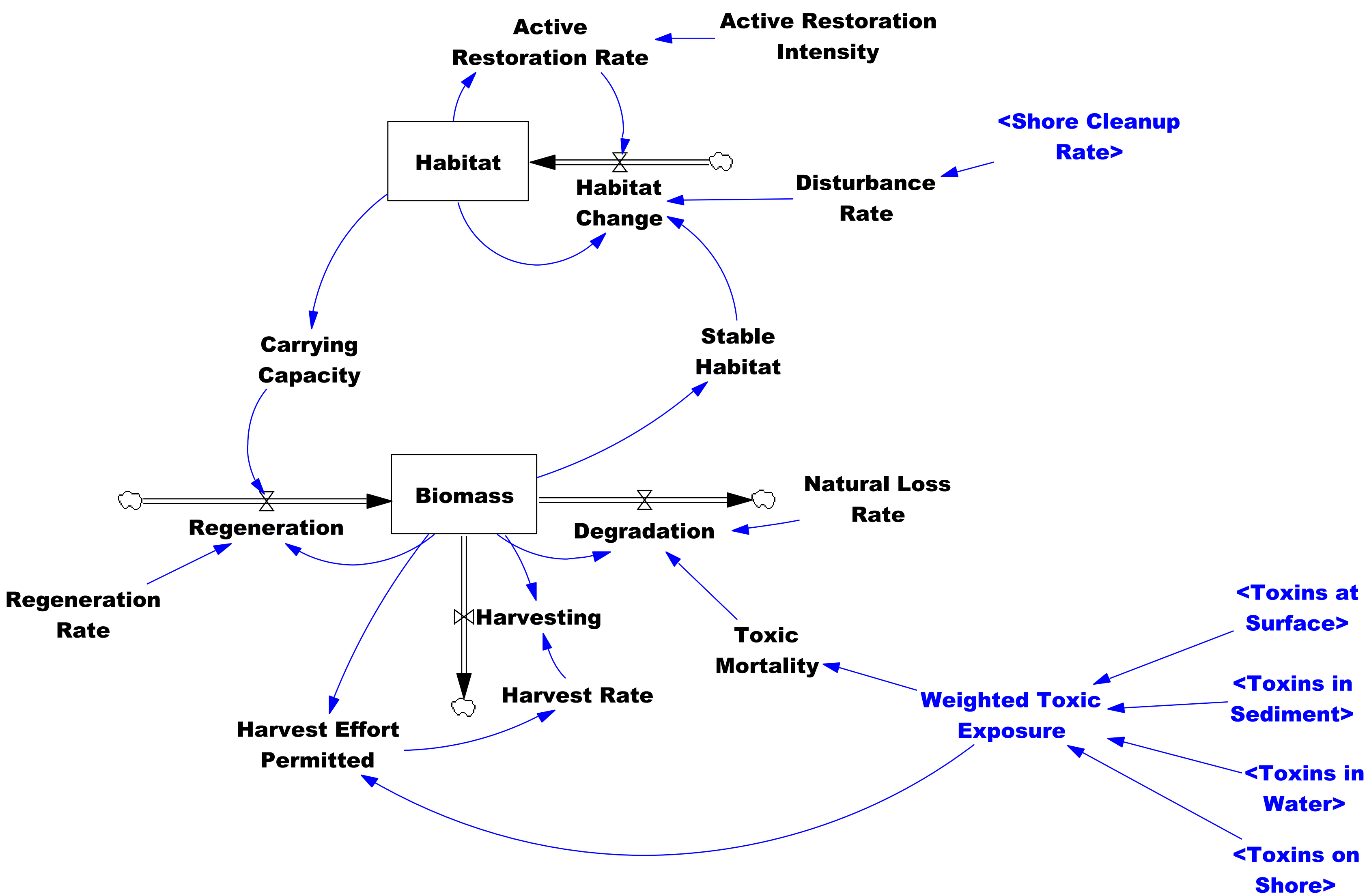

Figure 28: Ecosystem sector, with biomass and habitat states. Blue variables indicate inputs from the physics sector.

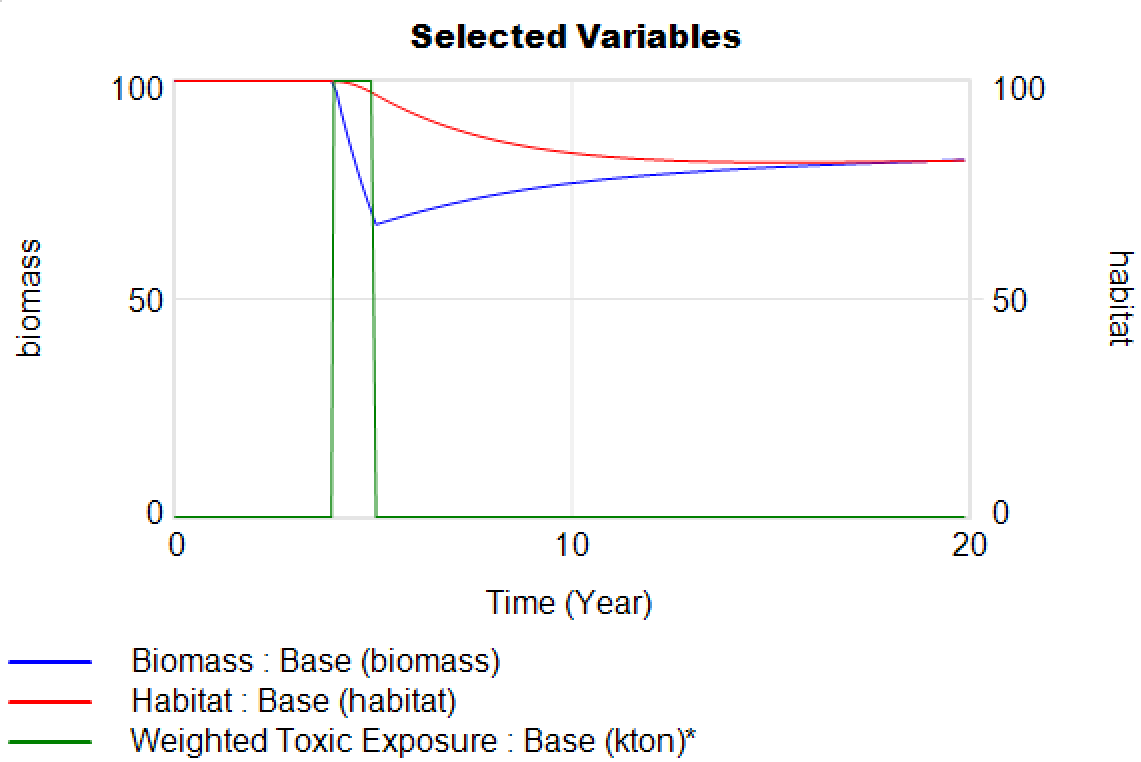

Figure 29: Biomass-habitat response to a temporary toxic event. Green: an externally-imposed toxic event with duration of one year. Blue: toxicity immediately reduces biomass via mortality. Red: reduced biomass leads to erosion of habitat, and therefore diminished biomass carrying capacity, preventing the system from returning to its original state.

Two policies are possible: active restoration of habitat, and biomass harvest. Harvest takes a "normal" fractional rate of biomass, unless the presence of toxins above a user-specified threshold indicates that fishing should be diminished. As for boom deployment, this is a continuous, nonlinear function rather than a binary decision, reflecting the fact that many regions facing different exposures are aggregated. Restoration is a user decision, and is costly.

Human Health

This sector captures effects of exposure to oil and its economic side-effects on human health. There are immediate, acute health effects driven exposure to toxins, as well as delayed chronic effects. Each is driven by a dose-response curve that could be (but has not been) parameterized to data or more detailed models. Mental health is represented by a first-order model with simple regeneration and degeneration processes, driven by stress from health and economic factors. Poor mental health is also a contributor to poor physical health. Like the ecosystem model, the health model can have a tipping point such that excessive toxic exposure or economic hardship can drive the system into a degraded state, from which it is difficult to return.

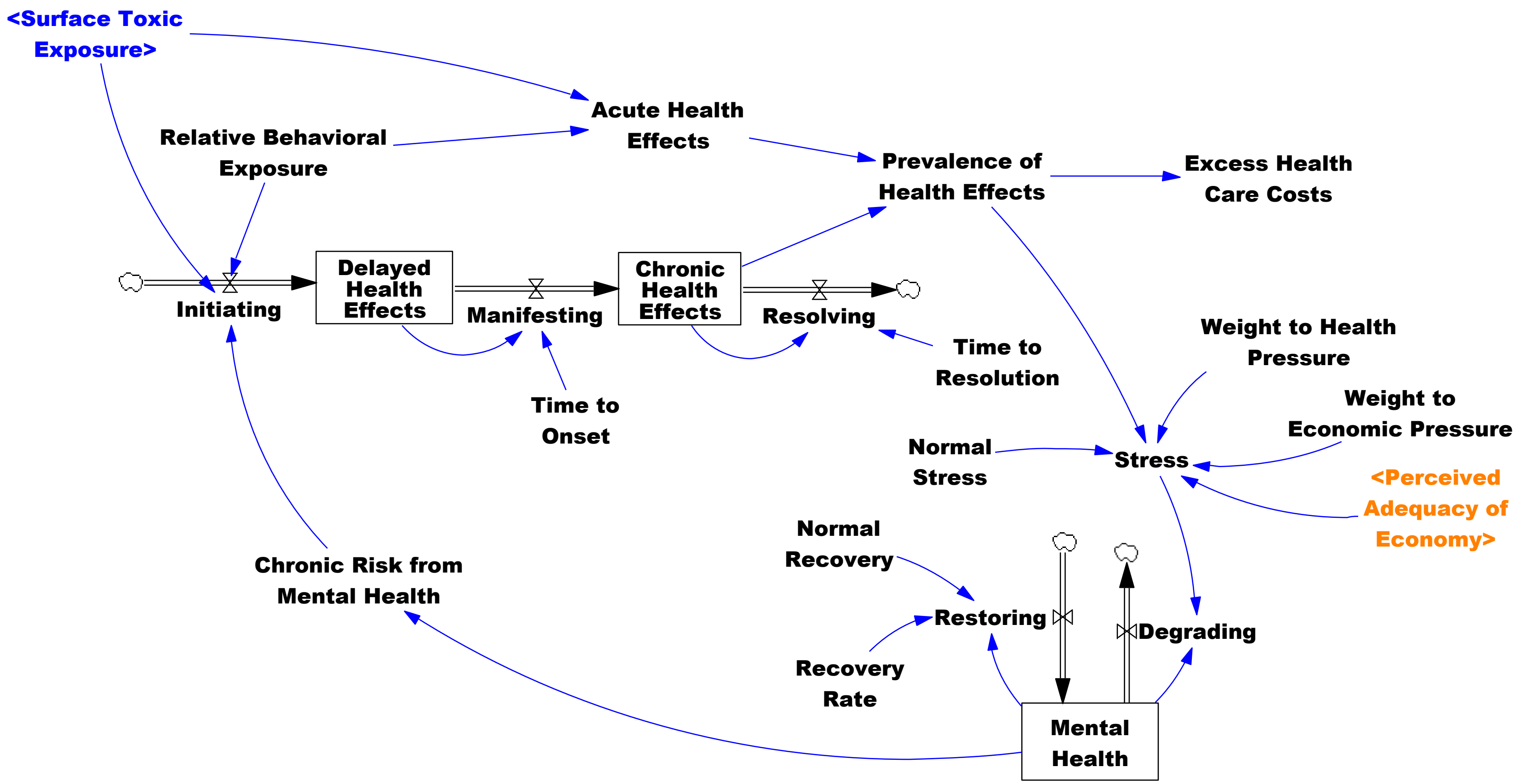

Figure 30: Health sector. Blue: toxic exposure from physics sector. Orange: mental health exposure to economic impacts in the socioeconomic sector.

Socioeconomics

The socioeconomic sector primarily captures activity in coastal economies. Economic activity is a function of cleanup expenditures, the value of ecosystem harvesting, and tourism. A multiplier captures spillovers to other sectors. Productivity is also important; it is influenced by mental and physical health as well as human capital build through educational investments. This creates another possible tipping point dynamic: if diminished activity or excessive health care costs make education unaffordable, diminished human capital will reduce long term productivity, and therefore value, creating a kind of poverty trap.

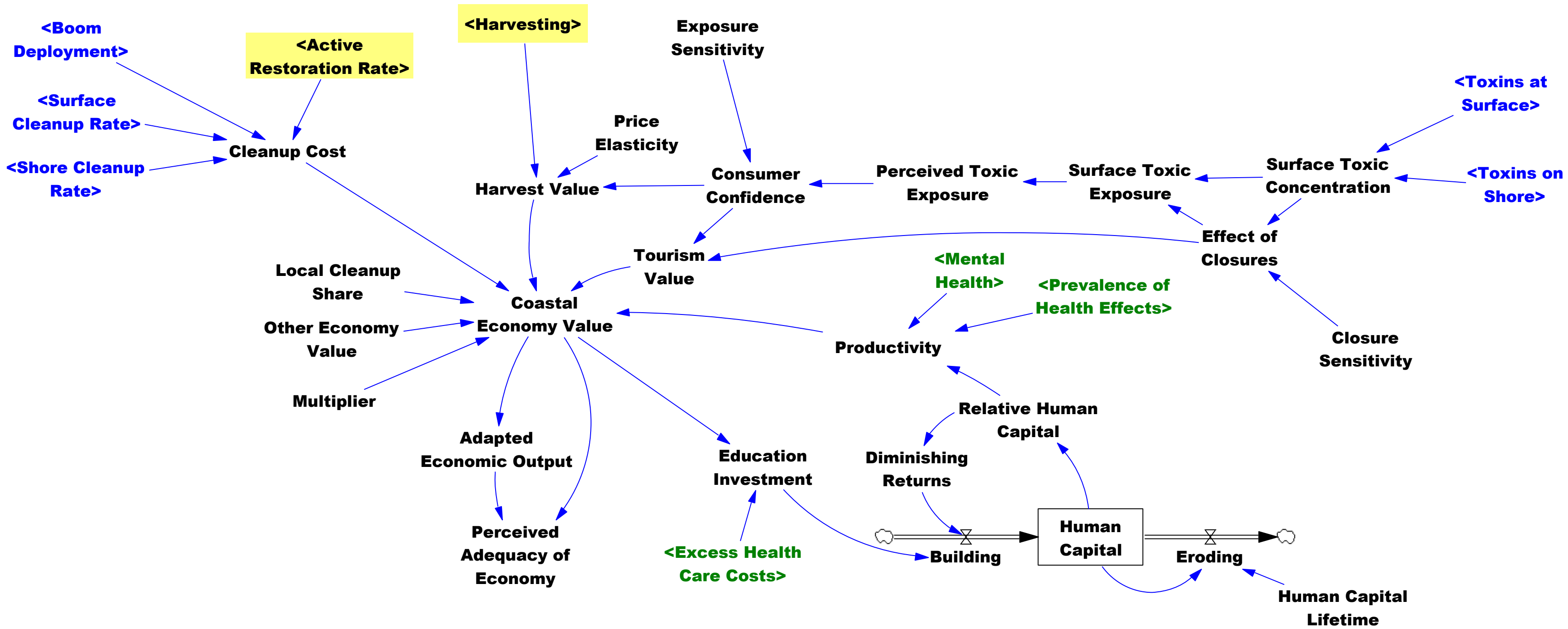

Figure 31: Socioeconomic sector. Blue: cleanup costs and toxin drivers of fishing and tourism closures from the physics sector. Yellow: biomass harvest and habitat restoration costs from the ecosystem sector. Green: health care costs and productivity effects from the health sector.

Stakeholder Perspectives

A simple control panel permits experimentation with the model and review of results from multiple perspectives. Figure 32 and Figure 33 illustrate application to three simple scenarios. The blue and red scenarios are spills without any response. In the blue scenario (labeled NoFeedback), feedbacks between health and the community-economy are inactive. The economy does not influence mental health, and health does not affect productivity. In this case, the harm to the coastal economy from the spill is modest, primarily because productivity remains constant. In the red scenario (labeled Base), these feedbacks are active. The community-economy-health feedbacks amplify the modest direct impacts of the spill, leading to severe economic and health effects. The economic harm to communities is further amplified by budget constraints, as spending is diverted from productive investments in human capital, degrading future productivity.

In the green scenario, use of dispersants increases the toxicity of oil, but reduces transport to the surface and shore. Cleanup efforts and booming further reduce the transport of toxins into the most sensitive environments. As a result, biomass and habitat damage and health effects are dramatically reduced. The tradeoff for these benefits is large cleanup costs (Figure 33, bottom right panel).

Uncertainty

Since little effort has been devoted to this model to date, its results are at best highly uncertain. But even if it were extensively calibrated and validated, much residual uncertainty would remain. Figure 34 illustrates an approach to uncertainty via Monte Carlo simulation, with a few key parameters draw from (arbitrary) probability distributions. In a fully developed model, a similar approach could be used to give stakeholders an appreciation for the uncertainty in tradeoffs and decisions, and to seek policies that would perform robustly in the face of unkowns.

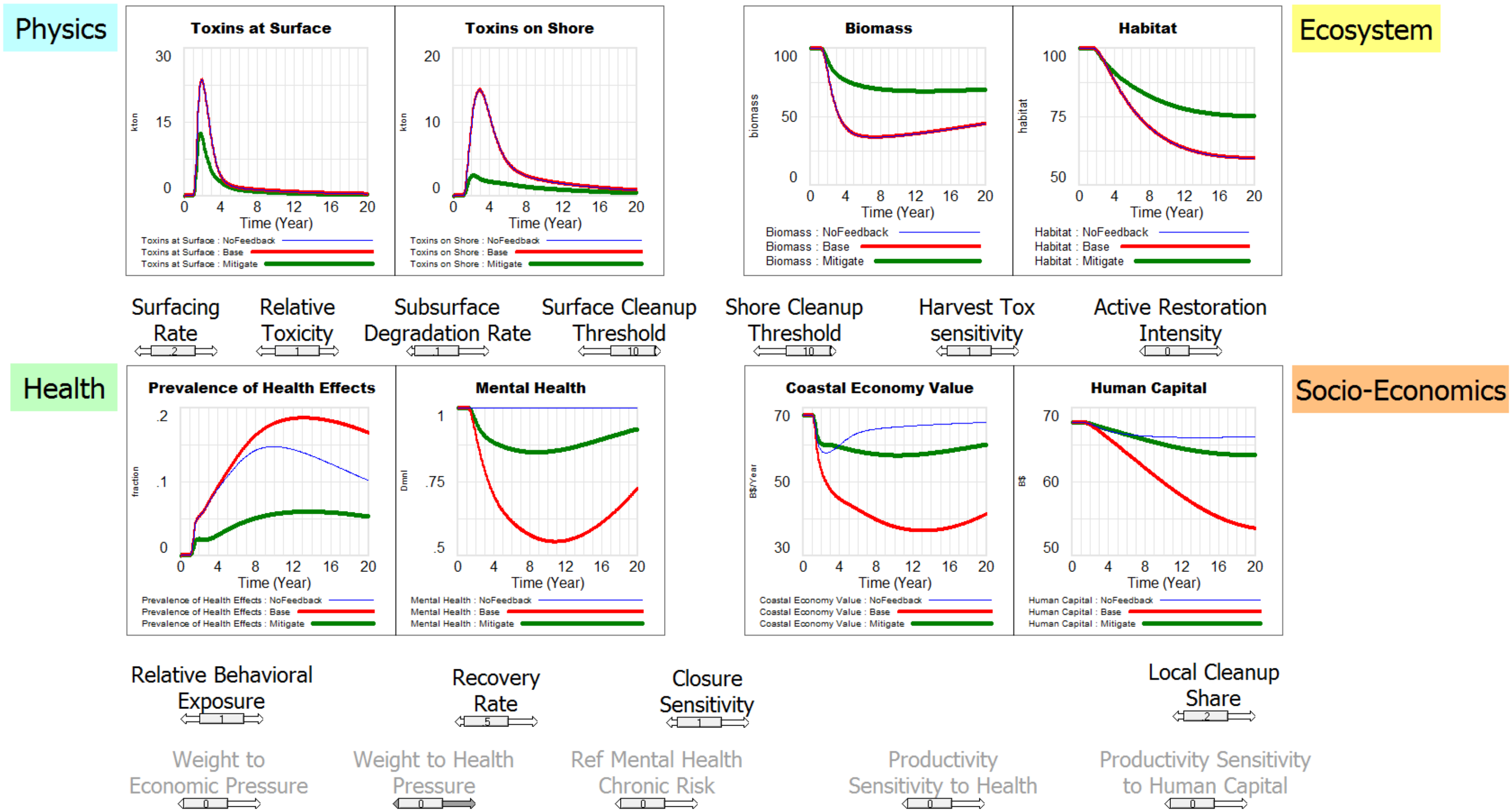

Figure 32: System states control panel.

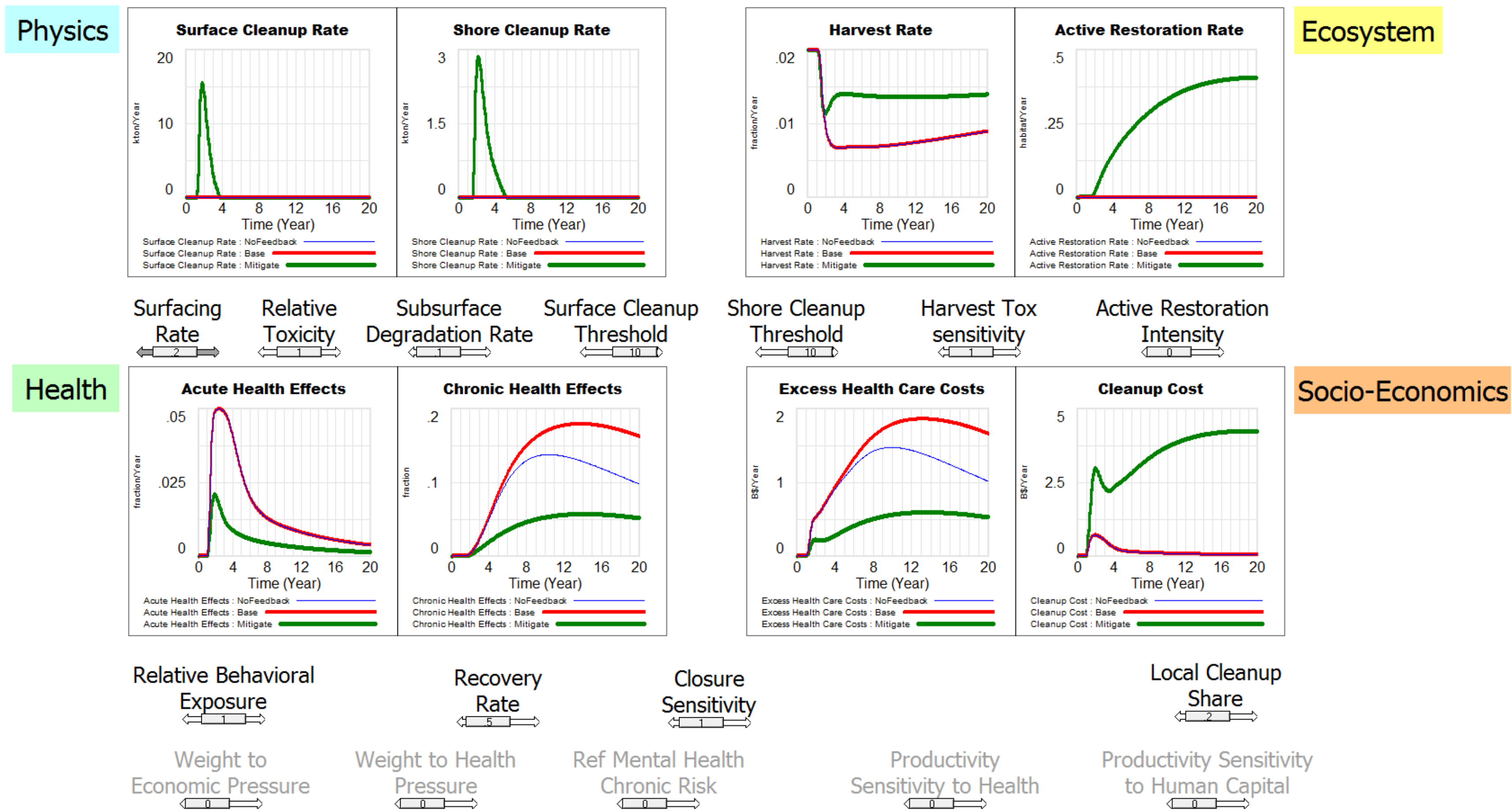

Figure 33: System rates control panel.

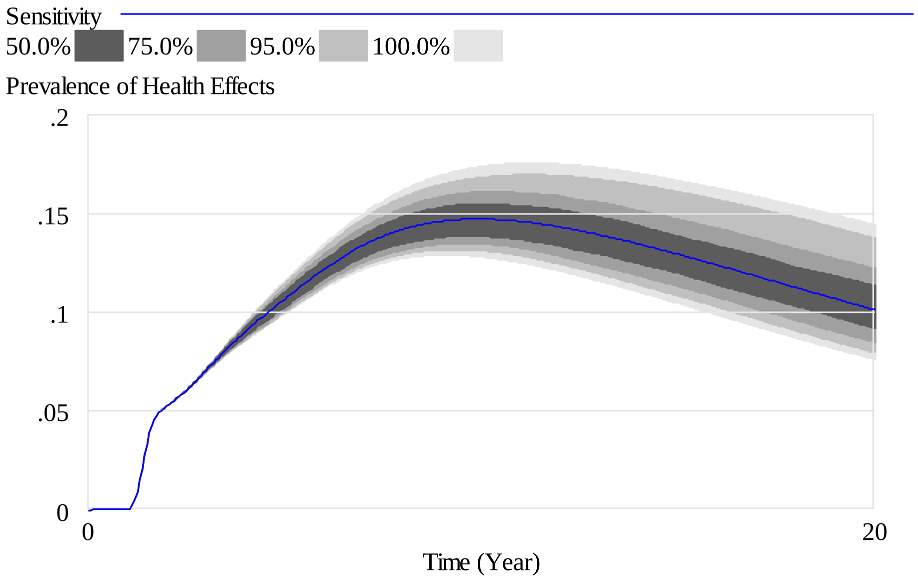

Figure 34: A sensitivity simulation, showing confidence bounds for health effects.

Extensions

This minimal metamodel would support an approach complementary to federation of detailed domain models. The top-down approach would support analysis of new kinds of long term strategic questions, such as determining the optimal level of effort devoted to spill avoidance. It would also permit the development of linkages to broader domains of great importance to the future of the Gulf, such as coastal development and climate change.

An enhanced top-down framework could also be the basis for a reusable component architecture. A researcher could replace one or more aggregate components with detailed models for a particular purpose, preserving the contextual value of the aggregate components with little additional work. The top-down model cannot exist without bottom-up, detailed research, which it needs for validation of its operational description of reality. Together, the two approaches could support a variety of new questions for models, adding value to existing research and improving quality of life in the Gulf.

Conclusion

A Chinese proverb says, "The best time to plant a tree was 20 years ago. The second best time is now." While integration has been proceeding opportunistically in some areas, and not at all in others, we believe that the time is right to make it a central focus, in the interest of closing loops in the science of the Gulf, placing new learning in context, and increasing the value of the research portfolio through stronger connections to decision making.

Acknowledgements

We at Ventana are grateful for the opportunity to lead this effort. To paraphrase, to the extent that we have seen far, it is by standing on the shoulders of giants. We could not have assimilated more than a tiny fraction of this material without the creative engagement of many inspiring researchers and the logistical and intellectual support of the GoMRI board.

Notes

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