Amalgamated Fisheries Modeling: A cross-scale approach to environmental dilemmas

The Open World project aims to better understand systemic problems in fisheries management by developing new cross-scale perspectives. Fisheries collapse is a global concern, affecting world food supply and economic prospects for fishing communities, and impacting ecosystem services and endangered species. Management structures have struggled with perverse economic incentives, multiple scales of uncertainty, and unintended policy consequences. Policies and dynamics at regional scales, including climate, trade, and migration networks, have a complicated relationship with local choices and behaviors. By improving our understanding of how scales and systems interact, we hope to reveal opportunities for more sustainable management.

This analysis starts with a spatially complex and institutionally specific model. For fish ecosystems, we hope to build models at both ecosystem and regional levels, allowing these to interact and each to inform possible scenarios. To model fisheries management, we will consider decision-making at the fishing community level, regional policy-making level, and the influences of various institutions and their decision-making procedures. To build these models, we plan to engage with fishing groups, scientists, policy-makers, and other stakeholders.

One goal of this research is to identify and understand potential policy leverage points. By unraveling the systemic forces that make fisheries management so intractable, we hope to also find opportunities for policy approaches that avoid opposition or counterproductive side effects. The work will start with a particular region and fishery, but the framework we build will allow models representing different fish species and policy mechanisms to be easily "plugged-in" to explore different contexts.

To study these interactions, the Open World project explores a powerful intersection between new theoretical foundations and modeling technology. Using theories of complex systems and statistical dynamics, we seek a stronger basis for multi-scale systems and new forms of coupling. This foundation supports the development of new frameworks for "amalgamated" modeling, which allows models at diverse scales and contexts to interact. Such a composite model also needs new theoretical and technological work to elucidate the driving principles behind the resulting dynamics.

The interactions between natural and human systems at different scales are central to many environmental and resource management issues. For example, global and regional policies place constraints on local behaviors, but the collective impact of these local decisions enters the large-scale systems that define those policies. A combination of coupling across scales using downscaling and aggregation, and the interplay between large-scale networks, constituent small-scale networks, and diffusion offers a way to understand these connections.

Models of economics and natural science are most effective at a given scale and context, but the boundaries between social institutions, between ecosystems, and between scales are rarely clear. Moreover, direct coupling of these models can both distort their accuracy and obfuscate the drivers behind their results. This project investigates how we can move beyond coupling, by looking at how systems and their component elements can overlap and mutually inform each other.

To support this research, the project will build a general framework for integrating an unlimited collection of models of social-ecological systems. This framework would provide an interface between models operating at different scales and contexts and according to different techniques and assumptions. The amalgamated approach allows different policy scenarios and ecological models to be easily substituted and compared. The composite system aims to be transparent in its operation, available as a rich foundation for other researchers, and open to new contributions.

Computational tools for validating and communicating the results become central in this framework. The Open World project will study new cross-scale metrics and statistical approaches to connect the amalgamated models and real world data. Equally important are tools that support more insightful communication, including ways to identify critical feedback loops and the most salient internal connections, helping to construct higher-level conceptual models. Finally, a key need for environmental problems is the ability to evaluate management leverage points, such as parameters or structures where small changes can result in pervasive differences in dynamics.

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Open Model for Climate Behaviors

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Motivation

Many of the human behaviors that drive climate change and environmental degradation are deeply embedded in our society, economy, and government, and are mutually reinforcing. Better modeling of human-natural systems can help in many ways:

- Analyzing feedback loops can help identify **leverage points**, where small policy changes can have pervasive impacts.
- Allowing models at diverse scales and contexts to interact can help scientists **integrate knowledge**.
- Interactive models can facilitate **communication** with policymakers and make complex problems intelligible.

The Open Model is a modeling framework aimed at these issues. The boxes right describe key components.

Applicability

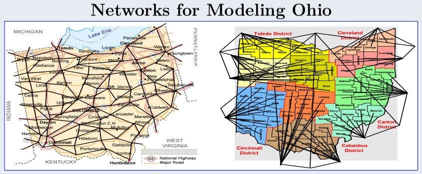
The proposed framework provides the greatest advantage for problems that are currently intractable due over-determined, reinforcing drives, and that are spatially heterogeneous. A wide range of environmental and public health issues fit this description, including **environmental degradation, agricultural practices in poor countries, obesity, substance abuse, groundwater use, and fishery management**, as well as situations fraught with **rebound effects** and cross-border shifts (e.g., **carbon leakage**).

The case studies below show some other projects that use the framework, in human and natural contexts.

Multiple Network Maps

Networks form the basis for models in the framework. Models can play out on multiple networks simultaneously, where different networks can be used to describe paths upon which stocks flow, can divide aggregates into classes, and can capture the network properties of natural-human systems.

Networks for Modeling Ohio

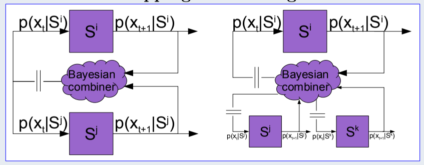


Two rough networks for modeling Ohio transportation behaviors. The left follows major roads, intersecting at major towns. The right represents the administrative hierarchy, from counties to the state. Also see the hydrological case study.

Overlapping Models

Models are inherently incomplete and different models overlap both conceptually and across scales. Combining them into one framework and allowing them to interact both improves the models and allows them to specialize. Bayesian methods are used to avoid runaway feedback.

Overlapping Model Diagrams



Conceptual diagrams of overlapping models. Left is a "simultaneous" model, where two models describe the same variable. Right is a "hierarchical" model, where an aggregate of values at one level mutually informs values at another level.

For a variable θ described by multiple models, each model provides both a PDF across values at a given time t when run in isolation, $p(\theta, \tilde{S}^i)$, and a distribution that includes feedback effects, $p(\theta, \bar{S}^i)$. The final distribution is

$$p(\theta|\cdot) \propto p(\theta) \prod_i p(\theta|\bar{S}^i)^\lambda p(\theta, \tilde{S}^i)^{1-\lambda}$$

Open Interface

As a research platform, a transparent, open modeling framework provides a context for models to be evaluated, communicated, and learned from.

An **Website Interface** would allow researchers to explore the model, run tests, and contribute models. For policymakers, the online interface would provide ways to interact with the model, see results, and outline scenarios.

In addition to allowing arbitrary models conforming to a Bayesian interface, a custom **Modeling Language** combines a units-aware equation-like syntax with network and GIS features.

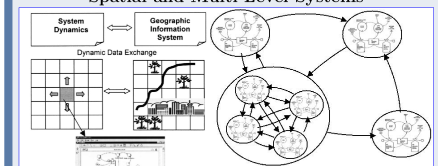
```
capacity = 1e10 [tons];
rate = 0.0077 [tons/year];
biomass = Stock(1e7 [tons]);
catches = TimeSeries('catches.tsv', [tons/year]);
biomass.IncreasesBy(rate * biomass * (1 - biomass / capacity)
  - catches);
```

An example of a model written for the framework, for modeling fish populations. The Networked Economics case study also uses this system.

Networked System Dynamics

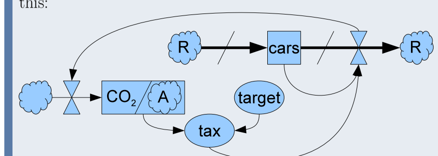
Spatial variation matters in ecological and economic models and for explaining tipping points. To help build spatially explicit models, relationships that drive temporal dynamics can be defined independently, and then applied to different GIS regions and networks.

Spatial and Multi-Level Systems



The spatial system dynamics architecture from [1] (left) is extended into a networked framework (right). Systems can be embedded within other systems at different spatial scales.

Continuing the example left of Ohio transportation, a simple model of networked transportation dynamics might look like this:

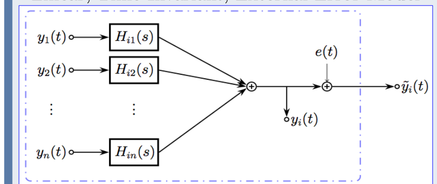


Here, $\{R\}$ is the road network, upon which cars move into and out of a region, and $\{A\}$ is the administrative network for aggregating CO_2 contributions.

Computational Tools

Large models can obscure the underlying causes of a system's behavior. Computational tools provide ways to identify the important mechanisms behind different behaviors, to evaluate the predictive performance of models, and to construct simplified models for analysis and communication.

Linear, Time-Invariant, External Error Model



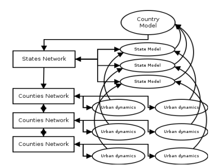
For analysis, a simplified, linear model is constructed, where the time evolution of each variable is assumed to be composed of linear combinations of the past histories of other variables. H_{ij} is the contributing transfer function between variable $y_j(t)$ and $y_i(t)$.

To determine driving feedback loops and high-leverage components efficiently, we construct an LTI model of transfer functions, informed both by data analysis (using "system regressions") and information from the models.

$$\begin{pmatrix} y_1[t+1] \\ y_2[t+1] \\ \vdots \\ y_n[t+1] \end{pmatrix} = \begin{bmatrix} H_{\theta_{11}}* & H_{\theta_{12}}* & \cdots & H_{\theta_{1n}}* \\ H_{\theta_{21}}* & H_{\theta_{22}}* & \cdots & H_{\theta_{2n}}* \\ \vdots & \vdots & \ddots & \vdots \\ H_{\theta_{n1}}* & H_{\theta_{n2}}* & \cdots & H_{\theta_{nn}}* \end{bmatrix} \begin{pmatrix} y_1[t] \\ y_2[t] \\ \vdots \\ y_n[t] \end{pmatrix}$$

Above, $H_{\theta_{ij}} * y_j[t]$ represents the convolution of a discrete-time series with a transfer function. This equation is analyzed in the frequency domain, where the equations simplify greatly.

Climate Behavior Model Structure



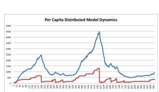
High-level structural architecture of the Open model for climate behaviors, described right.

As a first application, the Open Model will be applied to passenger driving behaviors. It will include the policies, businesses, materials, environment, and political economy surrounding and influencing the actions of American drivers.

To capture the multi-scale dimensions of this problems, the model starts with different models at a country, state, and urban level, connected through networks. Aggregate dynamics from the Country Model (based on [2]) are distributed through the States Network to each state's model (which is a modified version of the Country Model). The State Models relay stocks between each other through the States Network, and inform the Country Model. Each node in the State Network is associated with a Counties Network (that is, each state is divided into counties). The results of each State Model are further distributed to Urban dynamics models (based on [3]), by way of the Counties Networks.

By constructing a large model (with a minimum of 2000 variables distributed in space), capable of modeling leverage points at many levels, the most effective policies can be identified.

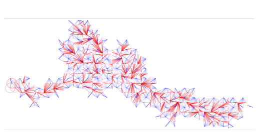
Case Study: Networked Economics



"Boom-bust" cycles in a networked generalization of the Solow economic growth model.

Economic growth is anything but smooth, but cannot be easily modeled without heterogeneous actors. By applying a traditional Solow growth model to a network of firms, a variety of dynamics can be demonstrated, including the "boom-bust" cycle, left.

Case Study: Hydrological Modeling



An efficient network map of a basin.

Snow and ice melt form significant contributions to river base flows throughout the Himalayas, but their contribution to seasonal and catastrophic flooding is unclear. A physical hydrological model was constructed on a grid, processing satellite-measured inputs into stream flows and floods. However, fine-grained modeling is computationally intensive for a large basin.

Left, the topography of a river basin is translated into a network for greater efficiency. Red represents channel flows; blue represents flow along the surface into channels.

Acknowledgments

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[1] Ahmad et al (2004). *Journal of Computing in Civil Engineering* **18**.

[2] Meadows, Randers, and Meadows (2004). *The limits to growth: the 30-year update.*

[3] Forrester and Karnopp (1971). *Journal of Dynamic Systems, Measurement, and Control* **93**.