AN OPEN MODEL FOR CLIMATE BEHAVIORS

JAMES RISING

Abstract. A system dynamics model of the behaviors that produce climate change can facilitate the identification of leverage points for effective policy. A new framework of system modeling and analysis is needed to support this model, and can be built by borrowing from the tools of network theory.

1. Introduction

Anthropomorphic climate change and environmental damage are among the most pressing issues of our time, and while an impressive array of new green technologies and strategies have been developed in recent years, the human behaviors that cause climate change remain frustratingly intractable. Within the United States, carbon tax and cap and trade legislation have stalled, environmentally damaging farm practices continue to be the norm, industry and agricultural subsides obscure the costs of business, and consumers continue to favor heavily processed, packaged, wasteful, and polluting products. Politicians are unwilling to advocate policy changes they fear would be unpopular; companies are hesitant to take climate change action on their own; and efforts on the part of consumers to avoid the unintended consequences of their purchases are difficult and time-consuming without the support of business and government.

These problems stem from systemic motivations deeply embedded in our society, economy, and government. Moreover, these influences are mutually reinforcing. If the U.S. raises its environmental standards, it can just encourage more imports from countries with lower standards. If years of research help make a new green technology economically attractive by saving businesses money, the total effect may backfire as businesses use the money saved to increase production and invest in dirtier industries (the rebound effect). See Rasmussen (1997) for an analogous situation for society-wide risk management. Localized policy changes can shift the balances in counterintuitive ways.

However, it is exactly these counterintuitive, systemic, and cybernetic effects that suggest the approach for this project. All complicated systems consist of interwoven feedback loops, often held in an overdetermined homeostasis. That homeostasis is characterized by both minimizing feedback loops, and maximizing ones. While the effects of some actions, whether they are new laws, citizen movements, or business decisions, are minimized and effectively dismissed, other changes will be reinforced and amplified. These “leverage points” are places where small changes can make big differences. Due to the structural nature of all systems, from ecosystems to economies, leverage points are pervasive (Meadows, 1997). In addition, the persistent pressures involved in Westernized societies, driven by economic growth and efficiency, place us in a “critical state” (Lux et al., 1998), which can accent small changes (Frette et al., 1996).

The behaviors that cause climate change, including the use of outdated energy-generation technology, wasteful agricultural practices, and unsustainable transportation habits, are mutually reinforced by our entire economic, social, and political systems. The goal of this project is to identify the leverage points in the social system surrounding U.S. behaviors that produce climate change and environmental damage. A very-high dimensional numerical model will be used to represent these behaviors, based on the techniques of system dynamics. In developing this model, there are a variety of opportunities to advance the field of human system modeling, using contributions from the field of network theory.

2. Applicable Literature

A wide range of models have been developed to understand and try to discover how to motivate pro-environmental behavior. The earliest models presumed that the problem was a lack of information, but these models proved to be an ineffective. Other authors have tried to look for the role of common-sense variables in determining pro-environmental behavior, such as rationality, competitive orientation, values, and satisfaction of needs, but these have had mixed results (Kollmuss and Agyeman, 2002). Hines et al. (1986) did a meta-analysis of 128 models of pro-environmental behavior and found evidence for knowledge of the issues, knowledge of action strategies, locus of control, attitudes, verbal commitment, and an individual sense of responsibility. However, the large number of proposed variables found to be poor predictors of actual behavior suggest the need for a model where inclusion of a variable does not neccesitate its use.

These models of motivation suggest a variety of variables that may be important components of societal behaviors, but the models themselves are less applicable. All of the models discussed by Kollmuss and Agyeman are agency models, as opposed to structuralist models. Redclift and Benton (1994) notes,

> One of the most important insights which the social scientist can offer in the environmental debate is that the eminently rational appeals on the part of environmentalists for 'us' to change our attitudes, or lifestyles, so as to advance a general 'human interest' are liable to be ineffective.... The great majority of individuals may be 'locked into' patterns of daily activity (such as private car use) which they know to be environmentally destructive. Only if the spatial separations of work, shopping, leisure and residence were changed, or if public investment into socialized trasport provision were greatly increase and transformed would individuals have a meaningful *choice* to make about transport options for themselves.

A number of exciting approaches are emerging to encourage pro-environmental behavior, including community social marketing for sustainability and deliberative and inclusionary processes or procedures. Social marketing has been shown to much more effective than education (McKenzie-Mohr et al., 1999) in promoting pro-environental behavior. This further suggests that particular habits or existing structures outweigh the effect of new information. Some of the most important results of this project may be used by the social marketing movement. Recently, deliberative and inclusionary procedures (DIPS) has emerged as a powerful technique, which engages citizens in decision-making as a way to empower, inform, and transform constituents (Bloomfield et al., 1998). This is an exciting development which will nonetheless not be deeply engaged in this project. Like other institutions, the expansion or contraction of the use of round tables and citizens juries will be modeled based on existing data, and the model will have the potential to identify them as particularly strong action points.

The literature on community psychology also concerns the role of complex systems on social change initiatives. However, the models used by community psychologists are typically linear and unidirectional, to the detriment of their ability to study the behaviors they are interested in (Hirsch et al., 2007).

This proposal will not give a basic introduction to the tools and methodologies of system dynamics, but interested readers may consult Forrester (1991) for background, Meadows (1997) for leverage points, Sterman and Sterman (2000) for model-making, and Senge (2006) for intuition. In addition to Ludvig von Bertalanffy's formative models of natural systems (1973), Jay Forrester's work in organizational dynamics (1961), and Donella Meadows's *Limits to Growth* (2004), the techniques of system dynamics have been applied to many fields relevant to this project, including urban growth and decline (Alfeld and Graham, 1976, Forrester and Karnopp, 1971), energy policy (Naill, 1992), environment management (Guo et al., 2001), public health (Homer and Oliva, 2001, Miller et al., 2006), and social change initiatives (Repenning, 2002, Hirsch et al., 2007).

In the last couple decades, system dynamics has grown to focus on small models, for the purposes of education and understanding (see Senge, 2006, Sterman and Meadows, 1985). Even large models, like the System Dynamics National Model, have been influenced by this trend. The National Model consists of over 2000 equations, after several proposed sectors were collapsed into just two, capital plant and consumer goods, for the purpose of clarity Forrester (1991). This project represents a departure from that literature: while system models have an important role to play in education and facilitating the development of mental models, the granularity necessary to identify small leverage points necessitates creating a model that will not be conducive to a full understanding. A discussion of the proposed size for this model is included below.

3. Approach

The U.S. accounts for 20% of carbon dioxide emissions, and almost four times the per-capita emissions of China. The international production of imported goods for American consumers is responsible for additional greenhouse gasses, deforestation, resource extraction, and waste. While global warming and climate change are by no means a problem solely of the developed world, we currently represent a disproportionate impact, and have a corresponding share of the responsibility. This project focuses on the American consumer, through the policies, businesses, imports, environment, and political economy surrounding and influencing their actions.

A large number of fields inform a study of the factors that influence our habits, from psychology to economics. The framework of system dynamics provides a number of advantages exploited by this work. System dynamics explicitly (and visually) describes feedback loops and policy conditions, which is eases the process of describing relationships, experimenting with policy changes, and illustrating the results. It provides quantitative and intelligible results, which can be displayed as histories of variable changes over time for different senarios and well-understood small-model behaviors. Finally, a variety of existing models, such as the World3 model used by Meadows et al. and Jay Forrester's urban dynamics model, are available as a baseline.

In this project, the nature of environmental behavior is very broadly defined as any institution which affects the status of environment variables. If the use of coal powerplants declines, that is taken to be a societal behavior, influenced by a variety of forces. In essence, the entire decision-making process (such as the agency model described by Ajzen et al. (1980)) is excluded from the model, leaving only influnces and results, for several reasons. First, decision-making is extrememly complicated and individual, and the principles of individual decision-making cannot be safely applied to an aggregated population. Second, causaity within a system is poorly defined, where the "effect" often influences the cause. Third, we are interested in the pragmatic effects of these decisions, not the process itself.

One weakness of system dynamics is that it is hugely aggregative. In system models, distinguishing even between demographic segments (say, children and adults) requires reproducing all of the relevant relations that influence the both, as well as creating the dynamics between them. In addition, system models handle space poorly, tending to treat a distributed stock, such as a working population, as a single lump sum.

This project attempts to combine system dynamical modeling with the emerging research on fractal network theory. The world of social interaction is a networked and a spatial world, where different rules apply to different regions. Without this added complexity, the model would not be able to function on a sufficiently fine-grain to identify the particular institutions at the heart of climate change leverage points. Rather than applying a single model to a system distributed in space, each region (represented as a node in a network) contains its own model. However, unlike climate models where each cell's model is independent except at its boundaries, certain properties of the various elements of the model can be shared between all of the nodes that use it. For example, a state's institution for monitoring water quality may influence many districts independently, but activities in each district draw from a single budget.

One property shared by each model component is its aggregate behavior. For example, pollution levels in each district in a state combine to form that state's aggregate pollution stock. Many of the same dynamics apply to pollution at both the district scale and the state scale, and the two values are related. This relationship between scales of resolution motivates this project's goal to build self-similarity deeply into its model framework. In human systems, many of the same principles and behaviors are exhibited at many different scales: globally, nationally, within an metropolitan region, and within a single institution. In many cases, data series are only available at one scale– such as the nation-wide scale– but similar dynamics (that is, self-similar models) apply to all scales. In network theory, this self-similarity is called a fractal structure. Statistically self-similar dynamics apply to all levels and societal institutions (Song et al., 2005). Within the research on climate prediction, the process of moving between resolution scales is called downscaling, and the literature on both dynamic and statistical downscaling can inform this process.

There is one more contribution from computer science used in this project: an open interface for contributions. To describe a large number of the factors that influence climate changing behaviors, this model may need to be immense. By creating a way for other researchers to contribute to it, along with providing a meta-analysis of those contributions to help in their evaluation and review, the project becomes both more manageable and more useful. As a platform for researches to run their partial models within a larger context, this framework can help to identify both strengths and contradictions between existing models of society.

Unlike climate models, the purpose of this behavoral model is not to predict future states. By capturing the relationships between constituative elements, in such a way that present dynamics can be reproduced, the model can serve as a guide for identifying leverage points. However, unlike many system dynamic models, that guide is not primarily intended for human audiences or direct education. By developing automated tools for analyzing the model and running experiments, the high-dimensional model can be analyzed to identify key elements, relationships, and loops which can significantly effect the nature of the whole system. Following Meadows, the system will consider the following potential points of leverage: changes in parameters, buffer sizes and flow speeds, the strength of feedback loops, and the structure of information flows (1997).

The remainder of this document focuses on the characteristics of the framework needed to support an open, self-similar, networked system dynamics model. Each component represents a variety of prior work, but their combination is one this project's significant contributions.

A Framework of Partial Models: : The full project consists of two major pieces: a framework, and partial models. The aspects described here are properly aspects of the framework, which forms the basis upon which relationships can be described and modeled. Because the model as a whole will describe behaviors in a large number of heterogenous regions, we say that the model as a whole is composed of "partial models", which overlap, interact, and reinforce each other. Below, the terms "framework" and "partial models" are used to keep these aspects distinct.

Conditional Self-Similarity: A single system dynamic partial model can describe the behaviors of both aggregate variables as well as applied regionally by building the concept of self-similarity deeply into the framework (Morel and Ramanujam, 1999). Rather than explicitly duplicating the partial models to each of these and many other levels of specificity, the framework will use a kind of fractal analysis, where global dynamics are modeled with global parameters, but with the potential to "drill down" to arbitrary levels of detail, reproducing the self-similar behaviors, data permitting. At each scale, the dynamics can be modified (with a distinct partial model) to reflect that sub-region more accurately.

Monte Carlo Experiments with Stochastic Allotments: Sub-region dynamics depend significantly on what portion of the aggregate allotment of each variable they represent, and that data is only sparsely available. Although the tools of numerical analysis can produce a single solution to the large number of equations that describe this fractal structure, that considerable effort would give few benefits in for such a dynamic system. Rather, Monte Carlo experiments over a range of initial conditions would be needed to produce the spread of results (Liu and Chen, 1998). Given

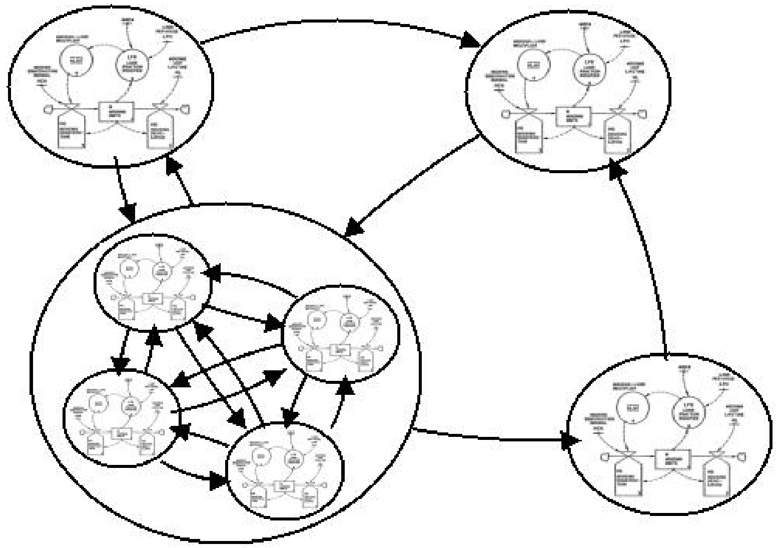
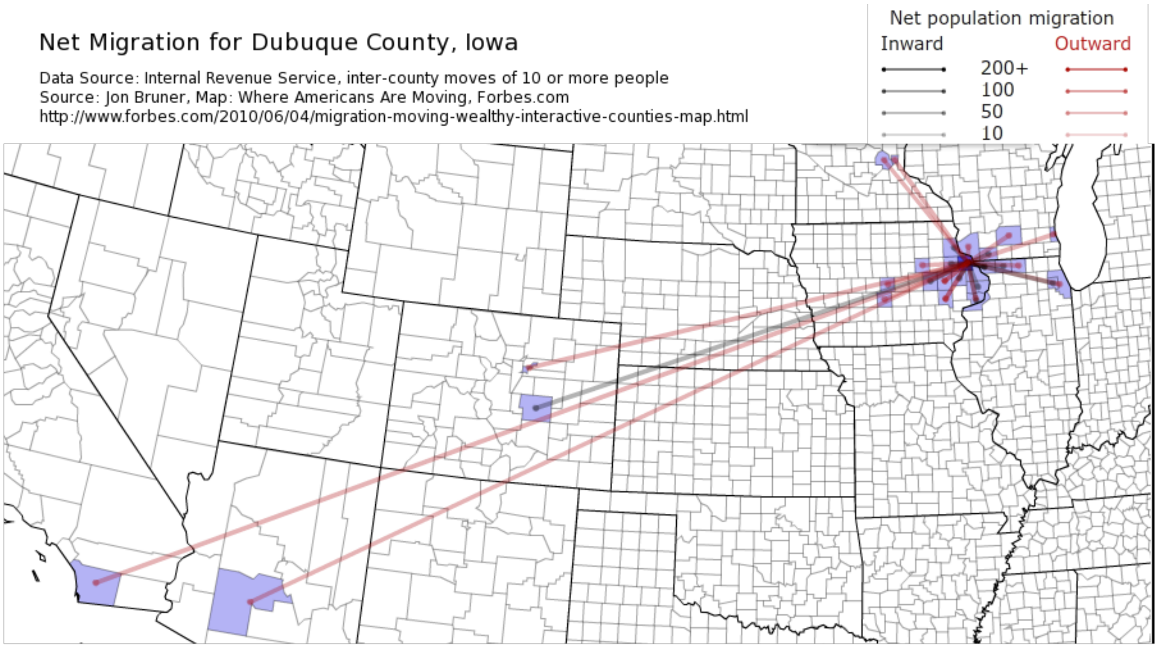


Figure 1. Self-Similarity in System Dynamics

that, there is little reason to simulate all regions simultaneously. Instead, a single "vertical" slice of the network can be simulated, by assuming previously computed allotments of aggregate values for all of the other sub-regions. This would result in a new data point, which then improves that sub-region's allotment distribution function (which could be represented just as a mean and a variance). Finally, some available data will represent "output" variables– variables that are related to the selected allotments by equations that are not easily reversible. Again, rather than using numerical analysis techniques to find solutions, which may themselves be distorted by inaccurate allotments, error terms will be calculated and used to weight the corresponding contribution to the sub-region's solution distribution.

Associated Time Series Data: : In the interest of both validating the model and determining its parameters, every system element will be able to be associated with a collection of time series data, with associated confidence values. In traditional system dynamic models, time series values, when used, are used to the exclusion of other dynamics, since the system would otherwise entirely determine the variable's value. In a framework with incomplete data, the two can be used in a complimentary fashion, where deviations from know data are allowed, registered in the confidence of the whole Monte Carlo run, and expressed within the system as a fictional pressure, along lines inspired by simulated annealing (Corana et al., 1987).

Multiple Maps: Different dynamics work upon different networks. For example, the United States can be modeled for climate change by placing it on a grid, but people travel on roads, where the effective distance between two points is determined largely by the properties of the roads between them. Information and culture flow in ways that are even more removed from the physical landscape, and the structures of many of these networks are readily available. These networks need not represent spacial distinctions: demographics and corporate relations can also be reflected on networks, easing the need to reproduce dynamics across the different groups. The framework will allow each region or institution to be represented by multiple maps, and elements within each partial model to play roles in multiple coexisting networks. The techniques of Dynamic Network Analysis may be applicable for this process (Carley, 2003).



Net Migration for Dubuque County, Iowa

Data Source: Internal Revenue Service, inter-county moves of 10 or more people
Source: Jon Bruner, Map: Where Americans Are Moving, Forbes.com
http://www.forbes.com/2010/06/04/migration-moving-wealthy-interactive-counties-map.html

Figure 2. Example district network: using I.R.S. data, each district node can be connected to other districts to form a densely-interconnected network.

Open Exploration and Contributions: The framework will have an interface on the Internet, where people can explore its predictions, download the entire system to experiment with its parameters, and upload partial models as proposed additions. The framework will use the libraries in FreeMat, an open source implementation of the MATLAB language and environment, so that making both data and model contributions is easy. Eventually, a visual interface, like STELLA or Vensim, can be added for additional ease. Group model building is widely used in system dynamics both as a tool for creating accurate models, and as a mechanism for social change (Rouwette et al., 2002).

Meta-Model Evaluation of Contributions: One of the purposes of the framework is to inspect the behavior of partial models to see how well they match historical data and other predictions Barlas (1996) describes a variety of techniques for validating models, some of which are readily applicable to an automated framework.

Meta-Model Identification of Leverage Points: The framework will also be able to intelligently seek-out and propose leverage points. A number of techniques could come into play, but the two simplest are hill-climbing algorithms and Monte Carlo methods. The system parameter estimation methods in Graham (1976) can serve as a baseline for this analysis.

Memetic Transfer of Partial Models: Most human behaviors are determined by habits and conceptions which reside in peoples' minds, and some of these ideas have the potential to spread and replace other ideas (Pech and Slade, 2004). Indeed, changing people's climate-change behaviors will partly happen only by this propagation of new ideas. Therefore, the regions of applicability for partial models must be able to change, and other partial models must have the capacity to describe this memetic transfer.

Integration with Climate Models: Actual changes in climate will have a strong effect on people's behavior, so climate prediction must inform the model as a whole. Initially, the framework can use pre-computed results from climate models, but climate change represents a coupled natural and human system, so ideally the integration would be deeper. Incorporating a general climate model (GCM) into this framework presents a considerable computation challange, but few conceptual difficulties. The three-dimensional climate grid of a GCM can be incorporated as another network map, and the dynamics in each cell are exactly analogous to the framework's partial models. The Community Earth System Model (CESM) would be a reasonable choice to modify and incorporate (Blackmon, 2003).

4. Research and Implementation Process

The process for proceeding with this project follows four overlapping phases: research, in conjunction with Columbia's classes on Sustainable Development; framework implementation, starting with a minimally working version; model development and tuning; and analysis.

The outstanding research questions include the following:

- What partial model should form the basis for the aggregate, which can then be modified and expanded, and what upon criteria should it be selected? The World3/2000 and System Dynamics National Model are likely choices, but the Department of Energy's National Energy Modeling System and the Redefining Prosperity Project's LowGrow model each have attractive components.
- What mathematical procedures can best address the dual problem of downsampling and time-series data usage? Both of these represent incomplete constraints on the values of the components, and their use diverges from classic system dynamics literature. Within normal system models, the model relationships produce all of the dynamics of the model, after a set of initial conditions. However, in this project, aggregate values (calculated at least partially using their own system models) place additional constraints: the sub-regions may redistribute aggregate stocks between them (along their connecting edges), but must remain true in aggregate. This represents new constraints on the system model, but far too few constraints to solve for a division of the aggregation without somehow merging these results with unconstrainted system's values.
- How to ensure that incomplete models do not distort dynamics? The model will evolve over time as more institutions are added. If, for example, the agricultural sector is modeled more fully than the industrial sector, the model needs to nonetheless

treat them equally. Even worse, when a relevant institution is entirely missing, but its effect are reflected in the aggregate data, the model must "fail gracefully", either by distorting results only at the institutional level, or by inferring the existance of unrepresented stocks if the existing dynamics cannot account for them.

- How best can the model be visualized? There are two incomplete conceptions of the resulting model, each of which strains current representational modes: from the perspective of a node, and from the perspective of a component. For a node on one of the networks, the model looks like a system dynamics model with additional constraints which come from the other networks in which the components play a part. For a component, the model is the collection of networks in which it plays a role– both the vertical hierarchy of scale networks (regional vs. subregional) and institutional networks. In a way, each component exists in an arbitrary collection of models, and while the component can sometimes take different values in different context (e.g., in a region it would have a different value than in a sub-region), all the values it takes are typically related. A further perspective could be focus on the system dynamics model, which may change from one region to another, but on a deep level those parts of it that do not change represent the actual same system even though they are viewed in different areas.

The framework implementation, which is already underway, can occur in the following steps:

(1) A minimal framework, developed in MATLAB, is needed that can combine both time-series data and system dynamical relations, and reproduce the dynamics of other research reliably when either or both are present. At this point, relationships from the baseline model can be reproduced and checked.

(2) A language for describing multi-level networks and self-similar system models will be developed in MATLAB, and incorporated into the dynamics framework. Incorporating these piece requires tools from climate model downsampling and Monte Carlo experiments.

(3) Within an object oriented framework, like C#, the concepts of a multi-level network, multi-network system, multi-system component, must be implemented and formalized. The MATLAB models can then be incorporated using the open source FreeMat library.

(4) Basic evaluation techniques should then be added, to ensure that partial models reflect the dynamics observed in data, and for tuning the parameters that knit together distinct partial models.

(5) A website with documentation and a system for contibuting to the model, is built, as well as a way for researches to peer-review and expand each other's models.

(6) Analytics are developed for finding leverage points: first to identify driving loops, then to suggest key parameter, and finally to propose structual adjustments. Both the tools and the ways they present their results will need to be refined to make them most useful.

(7) Extensions of the model framework, such as memetic transfer and climate coupling, can be explored.

It is difficult to estimate how many elements would need to be involved, but the following gives some sense. The 30-year update to the model for Limits to Growth consists of only 283 variables (stocks, equations, parameters, and outputs) while the System Dynamics National Model has over 2000. The monumental *Encyclopedia of World Problems and Human Potential* has identified 56,135 "problems", ranging from *Loss of cultural diversity* to *Youth gangs*, and identified within them 2,675 environmental feedback loops, "problems that are implicated in many negative feedback systems concerning the natural environment". If each of those were properly modeled, that would represents thousands of opportunities to break the cycle of environmental destruction. If one looks at institutions to capture the size, the range is similarly huge. There are approximately 495 departments and agencies in the federal government.[1]. Many of these manage, monitor, or influence either at least one relevant specific stock or flow, or at least one scale-independent stock or flow. However, the number of internationally opporating NGOs is much greater: the Yearbook of International Organizations lists 34,995 internation NGOs and IGOs.

The use of self-similarity greatly facilitates modeling these organizations, but it remains a daunting proposition. A model on the order of the National Model would capture many of the important dynamics that drive climate change, and combining this with self-similar networking and regional data would allow one to identify particular regions that might act as linchpins in the climate system. Incorporating more variables would not make the simulation unworkably slow, as can happen with climate models, since system dynamic models do not attempt to solve equations.

The framework provides the basis for a large number of experiments, each with a unique set of variables that it intends to measure. Different authors may place different emphasis on the production of CO_2 and other chemicals, the wealth or well-being of populations, and the health and diversity of ecosystems. Below is a potential measurement, and the associated tools used to maximize it.

The World Commission on Environment and Development defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". A reasonable proxy for the first is the Quality-of-life index, and the Living Planet index can reflect the second (both calculated at the present time). OLS Models will be used to estimate global indices based on United States variables. Ultimately, the model can be expanded to include institutions around the world, but this would increase the number of variables precipitously. The total "score", S_{SD} for a run of the model then is,

$$S_{SD} = int_{t=now}^{\inf} I_{QoL}(t) I_{LP}(t) e^{t/\tau} dt$$

integrated over all time of the simulation. The exponential term reflects the decreasing confidence in the models results. Since the model cannot be run forever, the final slope of

---

[1] Based on a count of the "A-Z Index of U.S. Government Departments and Agencies: Alphabetical list of organizations in the federal executive, legislative and judicial branches" at `http://www.usa.gov/Agencies/Federal/All_Agencies/Includes/Agency_Index.pdf`

the I_{QoL} and I_{LP} indices can approximate the total integral:

$$\tilde{S_{SD}} = int_{t=t_{now}}^{t_{end}} I_{QoL}(t) I_{LP}(t) e^{t/\tau} dt + e^{-t_{end}/\tau} \left(\tau^2 \frac{dI_{QoL}I_{LP}}{dt}(t_{end}) + \tau I_{QoL}(t_{end}) I_{LP}(t_{end}) \right)$$

References

Ajzen, I., Fishbein, M., and Heilbroner, R. (1980). *Understanding attitudes and predicting social behavior*. Prentice-Hall Englewood Cliffs, NJ.

Alfeld, L. and Graham, A. (1976). *Introduction to urban dynamics*. Wright-Allen Press Cambridge, MA.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System dynamics review*, 12(3):183–210.

Blackmon, M. (2003). Towards a community Earth System Model. In *EGS-AGU-EUG Joint Assembly*, volume 1, page 4984.

Bloomfield, D., Collins, K., Fry, C., and Munton, R. (1998). Deliberative and inclusionary processes: their contribution to environmental governance. *ESRC DIPs in Environmental Decisionmaking*, 17.

Carley, K. (2003). Dynamic network analysis. In *Dynamic social network modeling and analysis: Workshop summary and papers*, pages 133–145.

Corana, A., Marchesi, M., Martini, C., and Ridella, S. (1987). Minimizing multimodal functions of continuous variables with the simulated annealing algorithm. *ACM Transactions on Mathematical Software (TOMS)*, 13(3):280.

Forrester, J. (1991). System dynamics and the lessons of 35 years. *The systemic basis of policy making in the 1990s*, pages 1–35.

Forrester, J. and Karnopp, D. (1971). Urban dynamics. *Journal of Dynamic Systems, Measurement, and Control*, 93:128.

Forrester, J. and Wright, J. (1961). *Industrial dynamics*. MIT press Cambridge, MA.

Frette, V., Christensen, K., Malthe-Sørenssen, A., Feder, J., Jøssang, T., and Meakin, P. (1996). Avalanche dynamics in a pile of rice. *Nature*, 379(6560):49–52.

Graham, A. (1976). Parameter formulation and estimation in system dynamics models. In *The System Dynamics Method, 1976 International Conference on System Dynamics*.

Guo, H. C., Liu, L., Huang, G. H., Fuller, G. a., Zou, R., and Yin, Y. Y. (2001). A system dynamics approach for regional environmental planning and management: a study for the Lake Erhai Basin. *Journal of environmental management*, 61(1):93–111.

Hines, J., Hungerford, H., and Tomera, A. (1986). Analysis and synthesis of research on responsible pro-environmental behavior: a meta-analysis. *The Journal of Environmental Education*, 18(2):1–8.

Hirsch, G. B., Levine, R., and Miller, R. L. (2007). Using system dynamics modeling to understand the impact of social change initiatives. *American journal of community psychology*, 39(3-4):239–53.

Homer, J. and Oliva, R. (2001). Maps and models in system dynamics: a response to Coyle. *System Dynamics Review*, 17(4):347–355.

Kollmuss, A. and Agyeman, J. (2002). Mind the gap: why do people act environmentally and what are the barriers to pro-environmental behavior? *Environmental Education Research*, 8(3):239–260.

Liu, J. and Chen, R. (1998). Sequential Monte Carlo methods for dynamic systems. *Journal of the American statistical association*, 93(443):1032–1044.

Lux, T., Marchesi, M., and Bonn, U. (1998). *Scaling and criticality in a stochastic multi-agent model of a financial market.* Rheinische Friedrich-Wilhelms-Universit
"at Bonn.

McKenzie-Mohr, D., Smith, W., and Smith, W. (1999). *Fostering sustainable behavior: An introduction to community-based social marketing.* New Society Pub.

Meadows, D. (1997). Places to Intervene in a System. *Whole Earth*, 91:78–84.

Meadows, D., Randers, J., and Meadows, D. (2004). *The limits to growth: the 30-year update.* Chelsea Green.

Miller, R., Levine, R., Khamarko, K., Valenti, M., and McNall, M. (2006). Recruiting clients to a community-based HIV-prevention program: A dynamic model. In *Proceedings of the 24th international conference of the system dynamics society conference. Nijmegen, Netherlands.*

Morel, B. and Ramanujam, R. (1999). Through the looking glass of complexity: The dynamics of organizations as adaptive and evolving systems. *Organization Science*, 10(3):278–293.

Naill, R. F. (1992). A system dynamics model for national energy policy planning. *System Dynamics Review*, 8(1):1–19.

Pech, R. and Slade, B. (2004). Memetic engineering: a framework for organisational diagnosis and development. *Leadership & Organization Development Journal*, 25(5):452–465.

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety science*, 27(2-3):183–213.

Redclift, M. and Benton, T. (1994). *Social theory and the global environment.* Psychology Press.

Repenning, N. (2002). A simulation-based approach to understanding the dynamics of innovation implementation. *Organization Science*, 13(2):109–127.

Rouwette, E., Vennix, J., and Mullekom, T. (2002). Group model building effectiveness: a review of assessment studies. *System Dynamics Review*, 18(1):5–45.

Senge, P. (2006). *The fifth discipline: The art and practice of the learning organization.* Broadway Business.

Song, C., Havlin, S., and Makse, H. (2005). Self-similarity of complex networks. *Nature*, 433(7024):392–395.

Sterman, J. and Meadows, D. (1985). Strategem-2: A microcomputer simulation game of the Kondratiev cycle. *Working paper (Sloan School of Management); 1623-85.*

Sterman, J. and Sterman, J. (2000). *Business dynamics: Systems thinking and modeling for a complex world with CD-ROM*. Irwin/McGraw-Hill.

Von Bertalanffy, L. (1973). *General system theory*. George Braziller New York.