Judges' Commentary: Modeling Earth's Health

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Introduction

The general topic area for this year's Interdisciplinary Contest in Modeling (ICM)® was network science. This year's problem was an extremely challenging one that resulted in a decline in submitted reports for ICM from 1329 teams in 2012 to 957 teams this year. It is announced in this issue that network science and / or social network analysis will continue to be the topical area for next year's problem as well. So, for teams who want to prepare early for next year's contest, prepare by studying network modeling and assembling a team with that subject in mind.

The ICM continues to be an opportunity for teams of students to tackle challenging, real-world problems that require a wide breadth of understanding in multiple academic subjects. These elements of study are often included in the definition of network science—an emerging subject that blends structures, processes, data and applications from mathematics, computer science, operations research, sociology, information science, and

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several other fields. ICM problems are often open-ended, challenging interdisciplinary problems. This year's problem required significant innovation and creativity to build a viable model of Earth's health.

The complexity of this ICM problem and the short four-day time limit of the contest require effective communication and coordination of effort among team members. One of the challenging issues for ICM teams is how to best organize and collaborate to use each team member's skills and talents to tackle the complex nature of these problems. Teams that resolve this organizational challenge and cooperate well often submit solutions that can rise to the higher level of ICM awards.

This Year's Earth's Health Problem

There have been recent concerns about the growing stress on Earth's environmental and biological systems, but there are very few global models to test these concerns and what can be done though governmental policies to mitigate the stress. Therefore, society has been interested in developing and using models to forecast the biological / environmental health conditions of our planet.

The UN-backed Millennium Ecosystem Assessment Synthesis Report found that nearly two-thirds of Earth's life-supporting ecosystems, including clean water, pure air, and stable climate, are being degraded by unsustainable use. Soaring demands for food, fresh water, fuel, and timber have contributed to dramatic environmental changes, from deforestation to air, land, and water pollution.

Many studies conclude that current models do not adequately inform decision makers on global issues of public concern in these important high impact areas. While scientists realize that the complex relationships and cross-effects in the myriad environmental and biological systems are the driving forces in many of the issues of concern in Earth's biosphere, current models often ignore these network relationships or limit the systems' connections. The network-based complexities manifest in multiple interactions, feedback loops, emergent behaviors, and impending state changes or tipping points.

Although many warning signs are appearing, no one knows if Planet Earth is truly nearing a global tipping point. There are many factors that can be included in such a model—human population, resource and habitat stress, habitat transformation, energy consumption, climate change, land use patterns, pollution, atmospheric chemistry, ocean chemistry, bio diversity, and political patterns such as social unrest and economic instability. This year's ICM problem required the following:

Requirement 1:

The team had to build a dynamic global network model of some aspect of Earth's health by identifying local elements of this condition and appropriately connecting them. The model should have included a dynamic time element that allowed the model to predict future states. Possible models that were suggested were network nodes as nations, continents, oceans, or habitats; and network links could represent environmental influences or the flow or propagation of physical elements. Additional elements of this requirement were data availability to validate or verify the efficacy of your model and inclusion of a human element in the model to explain how human behavior and government policies could affect the model.

Requirement 2:

Next was the requirement to run the model to see how it predicts future Earth health and to test the elements of the model—not to use it for prediction or decision-making. Teams had to consider if the model could predict state-change or tipping points and help inform decision makers on important policies.

Requirement 3:

The third requirement was to analyze the model's network structure. This was included to see how network science could be utilized in a deeper, more theoretical, understanding of a global network.

Judges' Criteria

The panel of judges was impressed by the modeling in the submissions of many teams and fascinated by the variety of creative approaches that teams used to address the issues and questions that were posed by the problem. Many papers were rich in modeling methodology and some in modeling creativity.

To ensure that the individual judges assessed submissions on the same criteria, a judging rubric and guide was developed. The general framework used to evaluate submissions is described below.

Executive Summary

It was important that teams succinctly and clearly explained the highlights of their submissions. The executive summary should contain brief descriptions of both the modeling approach and the bottom-line results. The main sections of the report provide a more detailed explanation of the contents of the executive summary. One mark of an Outstanding paper was a summary with a well-connected and concise description of the approach used, the results obtained, and any recommendations.

Modeling

A well-defined measure of Earth's health was needed to initiate and build a viable model. Many teams used a pollution measure, such as carbon emission, CO2, heavy-metal pollution, air quality, or ocean water quality; others used a biology-based measure such as antibiotic health, food webs, or species extinctions. Other areas used to construct planet health measures were based on political, economic or financial data.

Some teams incorporated a game-theory framework in which the model pitted two competitors —Planet Earth against human destroyers, human technology benefits against technology's destructive forces, or the Earth's resilience against pollutants caused by humans. In many ways, these models resemble predator-prey models, with Earth filling the role of prey.

Still other teams used the conceptual framework of network connections and measured health by determining the probability of future effects within the context of currently-known data. For some teams, health was a scalar value, while others established a multidimensional vector with components such as land use and forest coverage, human population, economy, technological progress, political stability, and resource utilization. Still others used a multilevel approach with aggregation of measures at regional or local ecosystems, countries, continents, oceans, and earth levels.

The resulting mathematics included differential equation models resembling SIS / SIR epidemic models, neural networks, and discrete dynamical systems. Some teams used the explicit structures of networks or graphs to determine classic local or global network metrics, properties, or node clusters; in this case, critical assumptions like the directionality of influence and connection within the network lead to viable network models. Other teams ignored any network structure and performed classical data mining and element classification and discrimination; in this case, teams often found prioritization and ordering easier but their model offered little predictive capability.

No matter the modeling framework, the assumptions needed for these models and the careful and appropriate development of these models were important in evaluating the quality of the solutions. The better submissions explicitly discussed why key assumptions were made and how these assumptions affected model development. Stronger submissions presented a balanced mix of mathematics and prose rather than a series of equations and parameter values without explanation. One major discriminator was the use or misuse of arbitrary parameters without any explanation or analysis. Establishing and explaining parameter values in models are at least as significant as making and validating assumptions.

Probably the most challenging aspect of this ICM problem was the determination of the possibility or the effects of tipping points. The problem asked teams to assess if their model could predict state change or tipping points in Earth's condition in order to provide warning about global consequences of changing local conditions. Some teams ran simulations or performed data analysis to find threshold values or state change conditions. Other models included feedback loops that changed as model parameters or outputs changed. The judges recognized the difficulty in performing this analysis and rewarded strong tipping-point models.

Science

Teams often used environmental factors as proxies or indicators of planet heath. These highly sophisticated and complex dynamic processes are one possible type to model Earth's health. Some teams did effective background research and analysis of this aspect of the problem, and included elements of scientific analysis in their model, or described how their model could accommodate such capability had appropriate data been available.

No matter what modeling was performed by the teams, the interdisciplinary nature of this problem was fully revealed in its requirements and in the background investigation performed by the teams. The ICM students were exposed to many scientific fields in the context of their background research and the team reports required proper documentation of the team's research sources.

Data/Validity/Sensitivity

Once the model was created, the use of test data and checks on the accuracy and robustness of the solution helped some teams to build confidence in their modeling approach. Sensitivity analysis to determine the effects of assumptions and changing data and errors can be empowering to the modelers; this is especially true for highly-structured and powerful data-rich models like networks. Some network structures are highly robust and flexible, while others are fragile and highly sensitive to data. While this sensitivity analysis is a challenging element of network modeling, it was important to address this issue in the report, especially as it related to the effects of government policy making. This was another challenging element of the problem—how to use the model to inform and guide potential policy decisions. Teams that did this well quickly rose to the top of the judges' evaluations.

Strengths/Weaknesses

Discussion of the strengths and weaknesses of the models is where students demonstrate their understanding of what they have created. The utility of a model fades quickly if team members do not understand the limitations or constraints of their assumptions or the implications of their methodology. Networks are complex structures; therefore, the strengths and weakness are often hidden from direct view or full control of the modeler. Some of the better reports presented these elements despite these challenges.

Communication/Visuals/Charts

To clearly explain solutions, teams used multiple modes of expression including diagrams and graphs, and clearly-written English. A report that could not be understood did not progress to the final rounds of judging. Judges were often well-informed through the amazing array of powerful charts and graphs that explained both models and results. **Figures 1–3** show just a brief glimpse the richness of this kind of graphical analysis and reporting.

Recommendations

Teams were specifically asked to discuss how governmental policies could affect the results of their model and determine if there were impending state changes or tipping points in Earth's condition. It was important to include a recommendation of how modeling could inform decision makers on deciding on important policies as related to humans' effects on planet Earth. The ability of teams to evaluate the results of their analysis to make recommendations was important in identifying strong submissions.

Discussion of the Outstanding Papers

Many different approaches were used by ICM teams to model various aspects of the problem. As a result, the submissions this year were diverse and interesting to read. Overall, the basic modeling was often sound, creative, and powerful. Those papers that did not reach final judging generally suffered from two shortcomings:

- Some lacked clear explanation of the structure of their model. They provided some details but not a complete description of their model and its purpose.
- Others failed to connect their mathematical models to the aspects and basic elements of the science of their health measurement.

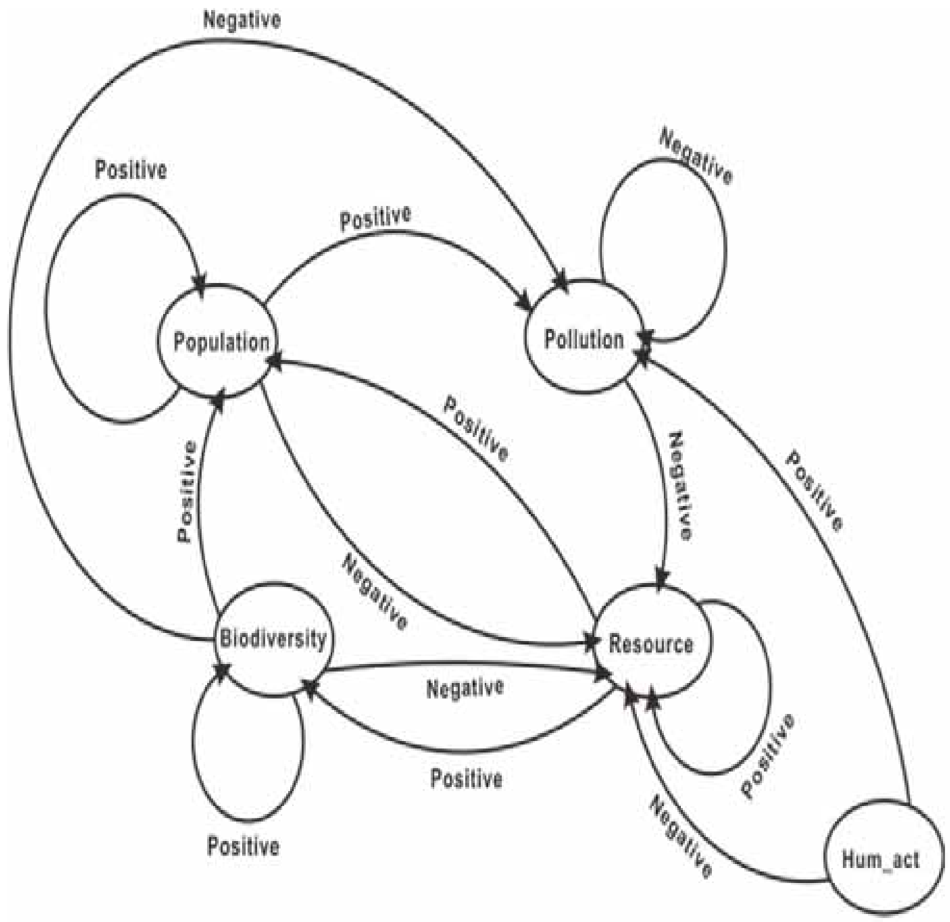

Figure 1. Some teams provided simple but informative graphic schematics to show the relationships and connections of the network framework of their models. This graphic is from Team 17802 from Sun Yat-sen University.

In general, incomplete communication was the most significant discriminator in determining which papers reached the final judging stage.

Although the outstanding papers used different methodologies, they all addressed the problem in a comprehensive way by embracing the complexity of the Earth's health issues that they had chosen. These papers were generally well-written and presented explanations of their modeling procedures. In several Outstanding papers, a unique or innovative approach distinguished them from the rest of the finalists. Others were noteworthy for either the thoroughness of their modeling or the power of their communicated results. Summaries of the five Outstanding papers follow.

Northwestern Polytechnical University: "Two-layered Coupled Network Model of Earth's Health"

The team's approach was to develop a two-layered coupled network model based on the Lotka-Volterra equations and reaction-diffusion. They

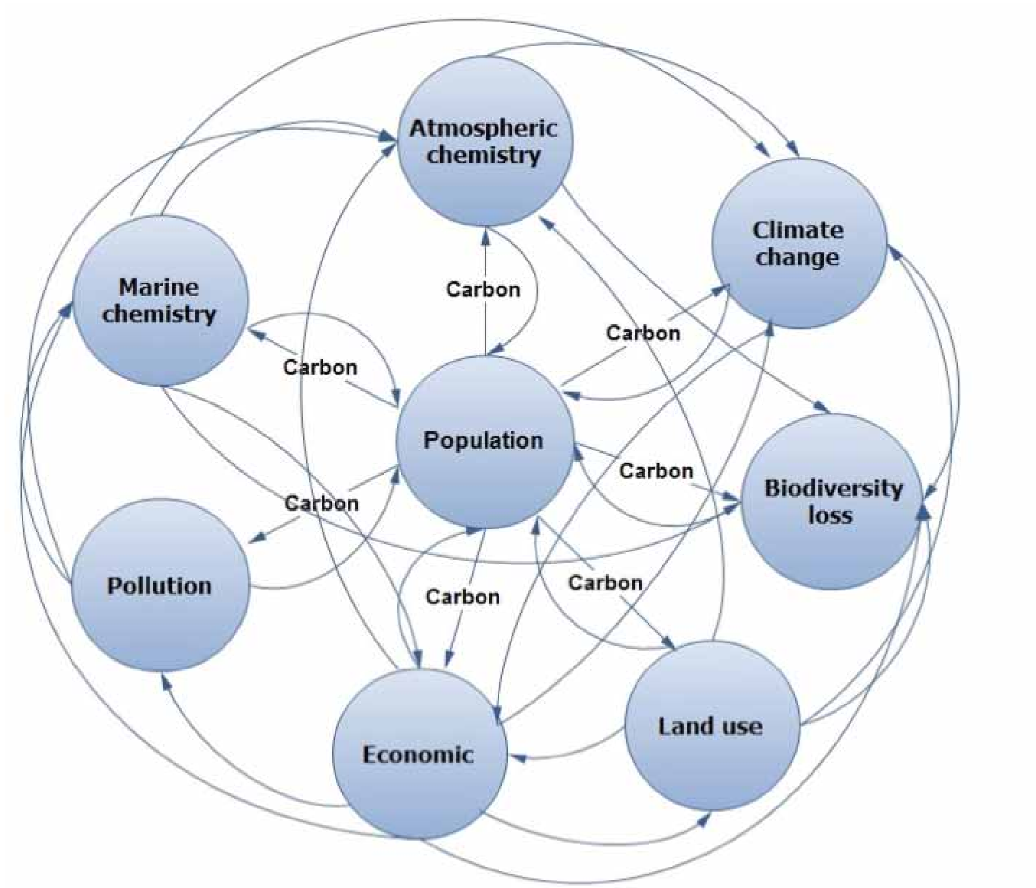

Figure 2. Another simple and informative graphic schematic. The graphic is from Team 19289 from Harbin Engineering University.

used their model to analyze, evaluate, and predict the biological and environmental health condition of Earth. The top-level nodes of their two-layer network are various ecoregions, selected through global geography and climate distribution. The subnetwork nodes for each region are seven elements of Earth's condition—population density, water, forests, air quality, biodiversity, climate change, and energy consumption.

The team developed a system of time-dependent differential equations to describe the interaction of all elements. The regional effects are then propagated among the neighboring regions in the top-layer network to analyze and forecast properties and structures of the global network. The team used data from a Yale University study to set the parameters using least squares. This complex dynamic model predicts the future trend of every element in each region, thus producing a measure of Earth's health. The team addressed the possibilities of tipping points by isolating their regional element equations and performing simulations. While identifying the possibility of tipping points, the team did not try to simulate all the conditions and possibilities, due to time and data constraints. According

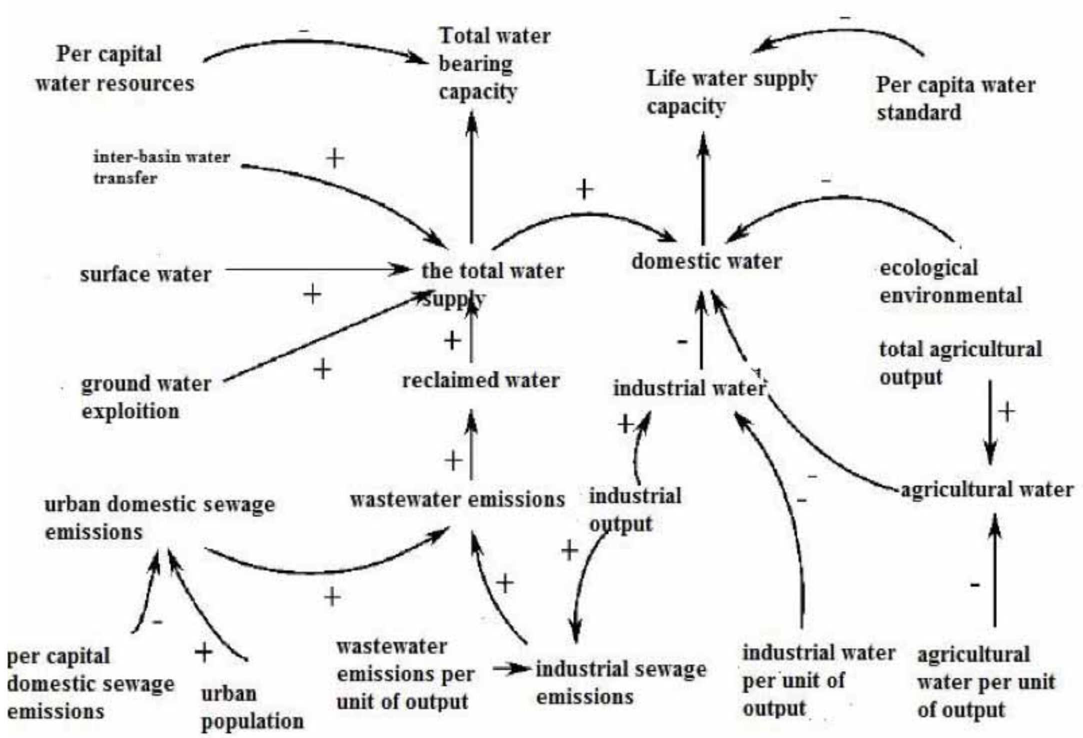

Figure 3. Some reports contained more elaborate conceptual flow diagrams, like this one from Team 17629 from Harbin Institute of Technology.

to their results, population density has the most effect on the remaining elements.

Of course, the idea of the team's work was to make suggestions that could be provided for government and decision makers based on changing parameter values and tipping points. The judges were impressed by the team's analysis of their network structure. They searched for importance of elements in the model by determining centrality measures of every element via network topology analysis. Their work demonstrated that forests were the most central structurally-based point of the network, while population density was the central process-based element. In their sensitivity analysis, the network model was converted to a stochastic model to test various components. In performing the analysis and synthesis of their network, the team was motivated to propose a new topology for a network with weights and a structurally and process-based conception of "influence degree" to evaluate influence capacity of the nodes.

The modeling and analysis performed by this team from Northwestern Polytechnical University were both innovative and powerful. The judges were impressed by their inclusion of so many perspectives and their ability to cope with and employ the complexity of their network model.

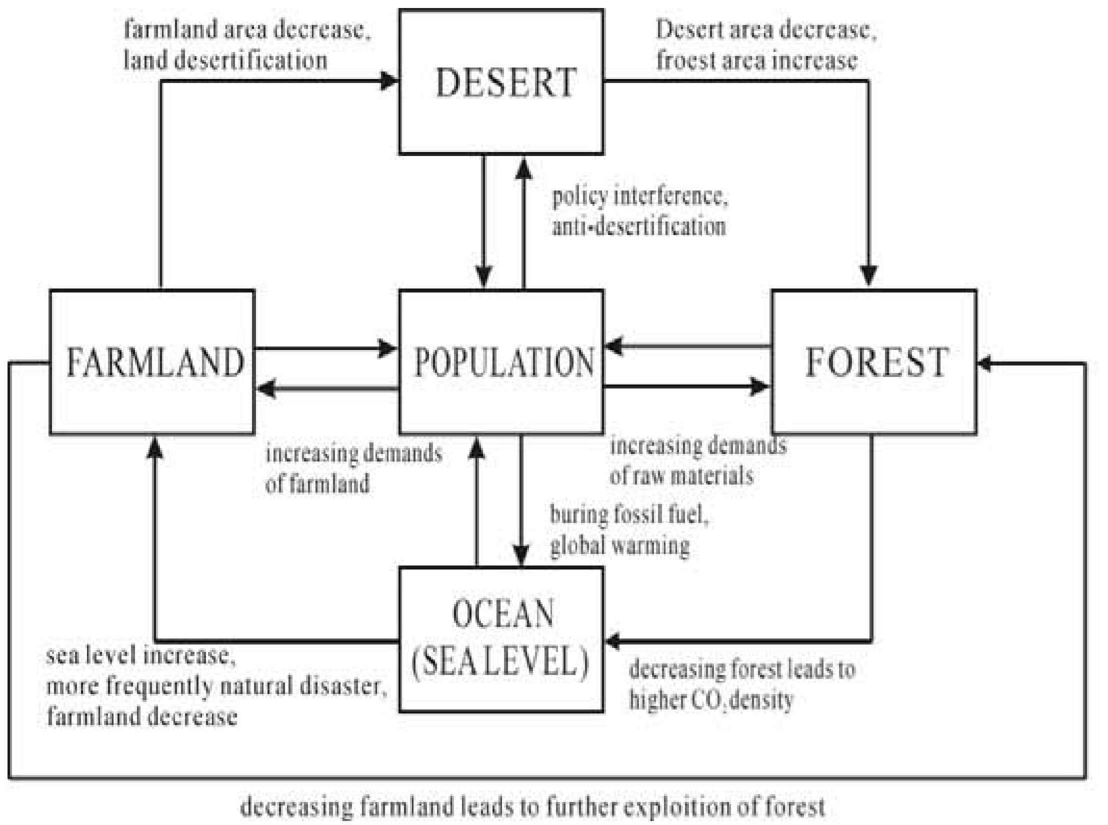

Figure 4. Other graphics showed detailed flow from various levels and elements in their model, like this one from the report submitted by Team 17785 from Harbin Institute of Technology.

Beijing University of Posts and Telecommunications: "Two-tier Communication Network Model of Global Health"

The team presented a two-tier network model as a communication network to study environment degradation caused by population change and air pollution. The top-tier network models the global environment, while the second-tier network (also referred to as the node tier network) models local conditions of smaller regions. The team followed the protocol design paradigm in communication networks to study the inner workings of the model using the standard machine learning technique. In particular, the team used the Bayesian Belief Network (BBN) to model interactions of the factors that could cause environment degradation with respect to the inherent trait of nodal area. They devised a nodal health measure to study local health conditions of the network following the analytical hierarchy process (AHP) approach, and used it to predict the tipping point at the node tier.

To study the global tier, the team investigated the difference of the influences of a node's active state and inactive state on signal transmission. They used the percolation ratio of the active nodes as the global health measurement. Using network theory they were able to obtain a global tipping point.

Finally, the team discussed what datasets were needed to validate their model. Toward this end, they applied the methodology of parameter estimation. And to the judges' approval, the team also discussed in detail how policies and models could impact each other.

The judges were impressed by the team's clear chain of thoughts in model constructions and analysis. The team presented an executive summary and a thoughtful background introduction. The team realized that it was difficult to validate their model because of the lack of any useful datasets. The judges liked the way the team handled this deficiency: The team did not hide this fact; instead, they stated this difficulty and explained what datasets they would need to validate their models and to analyze sensitivity and uncertainty. They provided justifications to each assumption, concept, design, and equation that they developed, and cited their sources. The judges also appreciated their theoretical approach and the creative thinking of using communication protocols, the BBN model, and percolation theory to study the behavior of the network. The models presented and analysis performed by this team were theoretically strong, and the judges were impressed by their clear report and rigorous solution.

Peking University: "Measuring Earth's Health by CO2: A Technology Diffusion Network Approach"

The team measured the Earth's health condition using carbon dioxide concentration and devised three interacting models to predict the future CO2 concentration level.

- The first model, called the Technology Diffusion Model, was the core model, where the nodes represented individual countries with CO2 emission-reduction technologies as measured through the Technology Index, and the links represented the diffusion of technology between countries.
- The second model, called the CO2 Regression Model, used datasets of economic growth and structural changes in energy consumption from the last two decades to predict the CO2 emission level.
- The third model, called the CO2 Absorption Model, was used to investigate the carbon cycle in terms of the nature's ability to absorb CO2. The team noted that the global temperature is proportional to the CO2 level, and an abnormally elevated temperature makes plants sick and hinders photosynthesis. When plants can no longer absorb CO2, no more organic matter will be produced, and the network model will reach its tipping point.

This dynamic global modeling approach allowed the team to study the Earth's complex ecosystem with a focus on the CO2 emission reduction technology. The team also provided a robust sensitivity analysis and showed how their model reacts when parameters were adjusted according to the changes of policies. Using their model, they were able to show that countries with more advanced economic and technological levels tend to have more influence on the global outcomes.

The judges were impressed by this unique solution. Unlike the previous two reports where two-layered network models were presented, this report provided a single-layered network model, where each equation was defined and analyzed. The report provided adequate explanations to the assumptions they made, and the team was able to validate their model.

Zhejiang University: "You Pollute, I Pollute!"

The approach taken by this team was to focus on ocean pollution as a marker for the Earth's health, and then subsequently to model the flow of pollution through eight regions, or nodes, of the global coastal water system. The team took a staged approach to modeling this system.

- First, they developed a Pollution Diffusion Model, adapted from the Princeton Ocean Model, where they defined eight key coastal regions as nodes in this network, and incorporated information on local pollution inputs, ocean currents, degradation of pollution through natural purification, and geographic distance between nodes, as components of their model. The goal was to analyze the performance of one region (node) and the interaction between nodes to ultimately evaluate how pollutants spread through the system and impacted the pollution levels of coastal regions across the globe.
- The second stage incorporated a Control System Model, which used a finite difference method to identify a solution for their Pollution Diffusion Model to predict future ocean health. A block diagram was used to represent the relationships in the system; and by varying the combinations of inputs in this system, the team simulated the outcomes of different scenarios, describing conditions of stability and drastic change—or tipping points. Some scenarios were based on different patterns of industrial developmental and pollution emissions in global regions, recognizing the importance of human and government factors and how these pollution inputs interact with their system. The team also considered a scenario of an unexpected major pollution event, such as a major oil spill. This gave them insight into the usefulness of their model for predicting outcomes of various real-world scenarios, environmental disasters, and different policy options. Sensitivity analyses were performed by testing the response of the system when eliminating particular nodes.
- The final stage of the modeling process introduced a Social Network Analysis Model to identify critical nodes in the ocean pollution system. The team appropriately selected a closeness centrality measure to identify "Influencing" and "Influenced" centrality scores for each coastal region, allowing them to rank the importance of nodes in terms of their

pollution input, and their susceptibility to being impacted by pollution diffusion in the system. They integrated the information from these models to describe how to make policy decisions that would impact water pollution and ultimately Earth's health.

The judges were impressed by many aspects of this paper, in particular the team's effort to address all of the requirements of the problem. They identified a creative marker of Earth's Health, ocean pollution, and did a good job of defining the diffusion of pollution through a networked system of key geographic regions. The team had a clear goal of predicting global and local levels of pollution in coastal waters, and used network science in an interesting way to understand the diffusion process, and how nodes both influenced, and were influenced by, this network.

The judges were also happy to see that the team evaluated the sensitivity of their model, as well as how their model performed under different scenarios with varying pollution inputs.

An innovative aspect of this paper was that the team considered the human and government effects in their models. The judges were also impressed by how the team linked these results to policy decisions, and discussed the usefulness of their model in informing policy change.

Finally, the paper was recognized for clearly outlining reasonable model assumptions, strengths and weaknesses of the model, and potential improvements. The potential usefulness of the model for predicting the Earth's Health and as a tool for policy change was made clear because the team outlined how data could be used to tune their model. What stood out the most was how the team used simulations and network analysis to show how changes in pollution inputs and in the structure of the network would have real implications on ocean pollution.

Rensselaer Polytechnic Institute: "Saving the Green with the Greens"

This group focused on economic systems between nations to predict Earth's Health, arguing that this information would be especially relevant to decision makers and could inform policy. Their paper presented a careful review of previous approaches to modeling environmental outcomes and provided a convincing argument as to why their Earth Damage Score (EDS), based on economic variables, was viable and useful. The team's strategy was data-driven by incorporating a range of national economic indicators from the World Bank. They used data on economic losses due to environmental factors to define EDS for nations over time; they also incorporated data on population, agricultural growth, GDP growth, and literacy rates into their models. The models were developed using innovative, incremental stages, starting with a linear regression approach. The judges found their comparison of simple economic models predicting the EDS to models that make use of environmental variables (e.g., carbon dioxide emissions, water pollution, etc.) to be very revealing. The team concluded that although their economic model was somewhat less accurate than environmental models, it performed significantly better.

This initial model was enhanced by incorporating a Geographic Network Model, where the nodes are countries, and links between them are defined based on countries' geographic proximity. The value of this model was increased by incorporating information on diplomatic relations and cross-country collaboration to further weight the ties between nodes. This rich network data is used to identify important aspects of the network structure: communities of nations who are closely connected in this system, countries who are the most central and prominent in this network, and countries with the most significant impact on the Earth Damage Score, by using a PageRank algorithm. The team used simulations to understand how key policy changes in some of the prominent nodes could have impacts on the global EDS. They identified key policy avenues—such as population growth—that are important triggers that might lead to overall system behaviors.

Their paper concludes with a summary of the strengths and weaknesses of the model and recommendations for further development of the model to improve its ability to predict global outcomes. The judges concluded that this economic model was a creative and useful approach that would be effective for motivating and informing decision-making and policy changes. The judges were also impressed by how the system of nations was defined using a complex network perspective. In particular, the team adopted a "multiplex" network approach, where links between nations were defined by more than one dimension—geographic distance as well diplomatic and social relationships. The paper also incorporated useful network statistics and presented a nice discussion of how different measures of network centrality were useful for their modeling approach. Finally, the paper was rated positively for having clearly identified and rationalized the assumptions of their model. This team effectively made use of graphics and tables to describe their model and its results.

Conclusion

Among the 957 papers, there were many strong submissions that made judging both exciting and a challenge. It was very gratifying to see so many students with the ability to combine modeling, science and effective communication skills in order to understand such a complex problem and build a viable model for its analysis. We look forward to next year's ICM, which will involve another problem in network science.

Recommendations for Future Participants

- **Answer the problem.** Weak papers sometimes do not address a significant part of the problem. Outstanding teams often cover all the bases and then go beyond.
- **Time management is critical.** Every year there are submissions that do an outstanding job on one aspect of the problem, then "run out of gas" and are unable to complete their solution. Outstanding teams have a plan and adjust as needed to submit a complete solution.
- **Coordinate your plan.** It is obvious in many weak papers that the work and writing was spilt between group members, then pieced together into the final report. For example, the output from one model doesn't match the input for the next model or a section appears in the paper that does not fit with the rest of the report. The more your team can coordinate the efforts of its members, the stronger your final submission will be.
- **The model itself is not the solution.** Some weak papers present a strong model, then stop. Outstanding teams use their models to understand the problem and recommend or produce a solution.
- **Explain what you are doing and why.** Weak teams tend to use too many equations and too few words. Problem approaches appear out of nowhere. Outstanding teams explain what they are doing and why.

About the Authors

Chris Arney graduated from West Point and served as an intelligence officer in the U.S. Army. His academic studies resumed at Rensselaer Polytechnic Institute with an M.S. (computer science) and a Ph.D. (mathematics). He spent most of his 30-year military career as a mathematics professor at West Point, before becoming Dean of the School of Mathematics and Sciences and Interim Vice President for Academic Affairs at the College of Saint Rose in Albany, NY. Chris then moved to RTP (Research Triangle Park), NC, where he served for various durations as chair of the Mathematical Sciences Division, of the Network Sciences Division, and of the Information Sciences Directorate of the Army Research Office. Chris has authored 22 books, written more than 120 technical articles, and given more than 250 presentations and 40 workshops. His technical interests include mathematical modeling, cooperative systems, pursuit-evasion modeling, robotics, artificial intelligence, military operations modeling, and network science; his teaching interests include using technology and interdisciplinary problems to improve undergraduate teaching and curricula. He is the founding director of COMAP's Interdisciplinary Contest in Modeling (ICM). In August 2009, he rejoined the faculty at West Point as the Network Science Chair and Professor of Mathematics.

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Jie Wang is Professor and Chair of Computer Science at the University of Massachusetts Lowell. He is also Director of China Partnerships of COMAP. He received his Ph.D. in Computer Science (1991) from Boston University, and an M.S. in Computer Science (1985) and a B.S. in Computational Mathematics (1982) both from Sun Yat-sen University. His research interests include big data modeling, combinatorial optimization, complex networks, network and cloud security, and wireless networks. His research has been funded continuously by the NSF since 1991. IBM, Intel, and Google have also funded his research. He has published over 150 research papers, authored and co-authored 5 books, and edited and co-edited 4 books. He is the editor-in-chief of the book series on mathematical modeling for the MCM / ICM contests, published by the Higher Education Press, China.