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Integrated Global Models

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Abstract

Integrated global models (IGMs) attempt to build quantitative understanding of the complex, dynamic history and future of human–environment interactions at the global scale. There is now a 30 year history of this approach. Over this period, computer simulation modeling has become a well-accepted technique in scientific analysis, but truly integrated simulation models — those that deal with the dynamics of both the natural and human components of the system and their interactions — are still relatively rare, and those that do this at the global scale are even rarer. This paper is a survey of past experience with IGMs to serve as the basis for discussion about their role in the IHOPE project. We analyze seven IGMs in some detail, comparing and contrasting their characteristics, performance, and limitations. The integrated global data base that IHOPE will create can greatly spur the development, testing and application of IGMs. At the same time, the development of IGMs can greatly facilitate thinking about what data needs to be collected. IGMs therefore will play a central role in the IHOPE project and deserve careful consideration.

Introduction

There is now a relatively long history of integrated global modeling (IGM) using computer simulations, starting in the 1970s with the World2 (Forrester 1971) and World3 models (Meadows et. al. 1972; Meadows and Meadows 1975). Since then the field has expanded, owing partly to the increasing availability and speed of computers and to the rapidly expanding global data base that has been created in response to increased interest in global climate change issues (Meadows 1985; Meadows et. al. 1992; Nordhaus 1994; Alcamo et al. 1998; Rotmans and de Vries 1997; IPCC 1992, 1995, 2001; Boumans et al. 2002; Meadows et al. 2004). Collectively, the applications of integrated global models constitute a relatively well focused and coherent discussion about our collective future. As Meadows (1985) has pointed out:

"Global models are not meant to predict, do not include every possible aspect of the world, and do not support either pure optimism or pure pessimism about the future. They represent mathematical assumptions about the interrelationships among global concerns such as population, industrial output, natural resources, and pollution. Global modelers investigate what *might* happen if policies continue along present lines, or if specific changes are instituted" (Meadows 1985, p. 55; italics added).

This chapter evaluates IHOPE's needs for further developing IGMs by identifying pressing questions to be answered by IHOPE, and presenting and discussing already available IGMs. We will also identify some of the gaps and challenges. Needless to say, this analysis is based on our personal views and limited experiences. The out-of-IHOPE emerging innovative IGMs could well have capabilities to deliver insights far beyond our current imagination.

The Need for IGMs

In today's world, human impacts on ecological life support systems are increasingly complex and far-reaching (Gallagher and Carpenter 1997). In this world, the emphasis needs to shift from addressing problems in isolation to studying whole, complex, interconnected systems and the dynamic interactions between the parts. Complexity implies that the whole is significantly different from the simple sum of the parts and that scaling (the transfer of understanding across spatial, temporal and complexity scales) is a core problem. Incorporating both biophysical and social dynamics makes these problems impossible to address from within the confines of any single discipline.

To address these problems, we must supplement our rapidly growing body of data and *analysis* about the natural world and humanity's role in it with a significantly expanded emphasis on *synthesis* of this information (Pfirman and the AC-ERE 2003) so that it can be better *communicated* and used by both the scientific community and by society. This synthesis can take many forms, but they all include some form of modeling. Models are defined as all methods of abstract representation of the real world, ranging from mental maps to conceptual diagrams to statistical correlations to dynamic computer simulation models. While a plethora of models exist about various aspects of humans in natural systems, they have only begun to be integrated and adequately tested against our rapidly expanding data bases and for their utility in addressing real world problems.

Integration of the natural and social sciences has lagged, due, in part, to the lack of a common language of discourse. Integrated modeling provides one possible method to bridge this barrier (Costanza et al. 2001). Achieving true "consilience" (Wilson 1998) between the natural and social sciences would be a giant leap forward in our ability to understand the world and manage our activities within it in a sustainable manner. The broader research community has already begun to work together to pose the kinds of questions that will need to be answered to understand humans in natural systems. As an example, a set of 23 system-level questions has been posed by the International Geosphere-Biosphere Programme's (IGBP) GAIM (Global Analysis, Integration and Modelling) project (now AIMES – Analysis, Integration and Modelling of the Earth System) in conjunction with the Earth System Science Partnership (ESSP) that will challenge an integrated 21^{st} century research community (See Box 1). They include analytical, operational, normative, and strategic questions. These questions can only be fully addressed by close collaboration between the social and natural sciences, as we are proposing in the IHOPE project overall, and especially in the integrated modeling activity.

Furthermore, the importance of considering scale depends on the boundaries set by the model. Whereas global aggregation may be appropriate for the impacts of CO_2 emissions on global climate change, simulation of regional impacts on water quality or quantity would not. A key question to be addressed by the global modeling community is how to capture both types of dynamics while maintaining a reasonable level of aggregation so as to keep the driving linkages clear and informative.

Box 1: Earth System Questions posed by IGBP/GAIM

Analytical Questions:

1. What are the vital organs of the ecosphere in view of operation and evolution?
2. What are the major dynamical patterns, teleconnections, and feedback loops in the planetary machinery?
3. What are the critical elements (thresholds, bottlenecks, switches) in the Earth System?
4. What are the characteristic regimes and time-scales of natural planetary variability?
5. What are the anthropogenic disturbance regimes and teleperturbations that matter at the Earth-System level?
6. Which are the vital ecosphere organs and critical planetary elements that can actually be transformed by human action?
7. Which are the most vulnerable regions under global change?
8. How are abrupt and extreme events processed through nature–society interactions?

Operational Questions:

9. What are the principles for constructing "macroscopes," i.e., representations of the Earth System that aggregate away the details while retaining all systems-order items?
10. What levels of complexity and resolution have to be achieved in Earth System modeling?
11. Is it possible to describe the Earth System as a composition of weakly coupled organs and regions, and to reconstruct the planetary machinery from these parts?
12. What might be the most effective global strategy for generating, processing, and integrating relevant Earth System data sets?
13. What are the best techniques for analyzing and possibly predicting irregular events?
14. What are the most appropriate methodologies for integrating natural-science and social-science knowledge?

Normative Questions:

15. What are the general criteria and principles for distinguishing nonsustainable and sustainable futures?
16. What is the carrying capacity of the Earth?
17. What are the accessible but intolerable domains in the co-evolution space of nature and humanity?
18. What kind of nature do modern societies want?
19. What are the equity principles that should govern global environmental management?

Strategic Questions:

20. What is the optimal mix of adaptation and mitigation measures to respond to global change?
21. What is the optimal decomposition of the planetary surface into nature reserves and managed areas?
22. What are the options and caveats for technological fixes like geoengineering and genetic modification?
23. What is the structure of an effective and efficient system of global environment and development institutions?

IGM Development

In IHOPE our approach to models needs to be pluralistic but evaluative. The rationale for any model is the scientific desire to capture the essence and to remove or reduce the redundant aspects of the system under study. What is essential and what is redundant and thereby what level of reduction is required, to a large degree, depends on the questions being asked. The result is a "model" of reality that is realistic to varying degrees. There is thus no one "right" way to represent reality in models, but we can judge and evaluate the relative quality of different representations for different purposes. Indeed, the level of spatial and temporal aggregation, as well as model assumptions and complexity, should be explicitly driven by the types of questions the model will be used to answer. We must also differentiate between models used for forecasting versus comparative scenario analysis. We recognize that no one model can fulfill all of these desires.

The environment, society, and the economy are each complex systems characterized by nonlinearities, autocatalysis, time-delayed feedback loops, emergent phenomena, and chaotic behavior (Kauffman 1993; Patten and Jørgensen 1995). Furthermore, these fundamental systems are intimately linked in ways that we are only just beginning to appreciate (Schellnhuber 1998). These complexities pose multiple challenges. Chief among these challenges is the recognition that to achieve the outcomes we desire it will be necessary to simultaneously incorporate several different perspectives. Clearly it will be necessary to incorporate the essential theories, tools, and knowledge of multiple disciplines across the spectrum from social to biological to chemical to physical sciences (Costanza and Jørgensen 2002).

However, it will also be necessary to incorporate the perspectives of nondisciplinary experts who have a strong stake — either directly or indirectly — in the achievement of particular outcomes. These stakeholders include policy makers who must formulate and justify frameworks for future development, resource managers who must interpret and implement those frameworks, and ultimately the communities who will either suffer or benefit from policies and decisions. The core approach of IHOPE will be to attempt to integrate and synthesize perspectives across all of the relevant disciplines and stakeholders.

Simulation modeling will play a pivotal role in helping these disparate groups to incorporate their individual perspectives and visualize a common future (Costanza and Ruth 1998; de Vries, this volume). Clearly, simulation models have the ability to integrate complex dynamics and distill them into readily digestible outputs. They also provide powerful means to communicate and educate, especially when models are used as vehicles to debate assumptions, explore alternative formulations, and discuss responses to different input configurations. In essence, simulation models can be used as "universal translators" that allow individuals with different backgrounds to access a model from their own perspective and then assess the output from this model in a form that can be understood from multiple perspectives. It is thus critical that models are well documented, summarized, and easily accessible to the general modeling community as well as to policy makers. Models also allow us to explore the realm of the possible, setting bounds on what we can realistically achieve with policy.

The IHOPE project will build on integrated modeling experience at multiple scales from local to global (Leemans 1995; Easterling 1997; Rotmans et al. 1990; Rotmans and van Asselt 2001; Rotmans and de Vries 1997; Krol et al. 2001; Costanza et al. 2002; Ehman et al. 2002; Boumans et al. 2002). IHOPE will allow us to accelerate the development and testing of models of humans in nature that yield better answers to important questions, such as those listed in Box 1. Of particular importance are questions that relate to the intertwined futures of human development and environmental quality at scales including the metropolitan scale, the watershed scale, the country scale, and the global scale. In addition to the general questions outlined in Box 1, more specific questions that the IHOPE project can address include:

- What types of demands on natural capital will be generated by land-use change and GDP growth, the provision of clean water, and increases in crops yields?
- In what nations are development trajectories most constrained by natural capital, and where are they most constrained by institutions or systems of governance?
- Can the OECD nations continue to grow at the same time that poverty is reduced in developing nations?

Testing and Evaluation

Significant effort in the IHOPE project needs to be devoted to testing and evaluating model performance relative to observed and reconstructed data and other criteria, and understanding and communicating uncertainty. Since the models are complex and the data is of highly variable quality and coverage (see Costanza, this volume), this is not a trivial task (Perez-Garcia et al. 1995; Tran et al. 2002). We do not wish to simply proliferate new models, but rather to develop a deeper understanding of the many ways in which models relate to data and better ways to judge the performance of models in order to winnow out the best performers for further development. The IHOPE participants have extensive experience in model assessment through inter-comparison of models with other models and with widely accepted benchmark datasets. The various inter-comparison projects have revealed weaknesses in model formulation, gaps in calibration and validation data, and new approaches that are applicable to other models. In addition IHOPE will contribute to building a "toolbox" of modeling and inter-comparison techniques for use by the broader community and participants in the proposed IHOPE activities. In one recent initiative, a catalog of model inter-comparisons was developed by IGBP/GAIM in conjunction with the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM). Although most of these comparisons were strongly focused on physical climate models and a biogeochemical carbon model and rarely included social aspects, this catalog can serve to alert others to what has already been done and thus eliminate redundancy in future efforts. It will also provide new modelers with an approach and baseline for model development and assessment.

Scenario Generation and Analysis

A key purpose of constructing integrated models of humans in nature is to facilitate quantifying the qualitative scenario narratives of the future under different assumptions about key driving forces, including alternative assumptions about institutions, technology, living standards, and policies (van Notten et al. 2003). Deciding which scenarios to run and interpreting the results are activities that require significant input from a very broad range of stakeholders (see de Vries, this volume). This will therefore be one of the IHOPE project's primary areas for stakeholder input and outreach and represents a major nexus with communities such as policymakers, nongovernmental organizations, and business. But it is also a primary research area, as it is inherently about the sensitivity of models to changes in underlying assumptions and parameter values.

A Survey of IGMs

Table 1 lists and categorizes some historical and existing IGMs according to several relevant criteria. As can be seen, the list is still quite short. This is partly because we have limited it to those models which are both *global* in their spatial extent, and *integrated* in their inclusion of both human and natural system components as endogenous variables. In the different international assessment processes, many other models have been used (e.g., Harvey et al. 1997) but most of them were not, or only partly, integrated. There are, of course many additional integrated models at the regional scale (cf. Costanza and Voinov 2003), and many additional global models that are not integrated in the sense above because they are assembled from a series of individual disciplinary models (e.g., Prinn et al. 1999). For example, global climate models (GCMs) have become quite popular and useful, but they do not include any endogenous human components. Human activities are usually an outside driving force on these models. The impact of greenhouse gas emissions, for example is modeled by setting the consequent changes in atmospheric concentrations or radiative forcing as new boundary conditions. Likewise, there are several global economic models that do not include natural systems (i.e., Leontief 1980; Hickman 1983).

Figure 1 illustrates the degree to which each IGM included in our survey captures important natural and social systems as well as the level of historic calibration attempted to date for each model. One can quickly see from this figure the range of coverage and complexity of natural and social components of the earth system. Note that in Table 1 we have lumped together (in most cases) models that are simply versions or updates of each other. Of course, this line is a bit fuzzy at times, since models eventually evolve into new forms, but the intention was to list only unique models. Web sites where one can quickly obtain more detailed information about each model are noted in Table 1.

Some interesting characteristics of this list, particularly for the purposes of IHOPE, include:

- Although the first models already emerged in the seventies, integrating spatial and societal dimensions only developed recently.
- The temporal range covered by all models is quite consistent and mostly covers the contemporary history and near future. In fact, all of the models listed are concerned only with the last 100 years (IHOPE's decadal time scale) and 100 years into the future.
- The degree of calibration and testing of the models against real world data is generally low. IHOPE can contribute significantly in this area by making a consistent integrated data base available for the global modeling community.
- The degree of human and natural system integration in the models has in general been only moderate. Again, IHOPE can contribute significantly in this area by providing a more integrated data base to start from.

Below, some brief observations on each of the major models that are still in active use are given, before concluding with some observations on the role of IGMs in IHOPE.

World3

The World3 model has been the subject of three influential books, beginning with The Limits to Growth (Meadows et al. 1972), continuing with Beyond the Limits (Meadows et al. 1992) and ending with the recent, 30 year update (Meadows et al. 2004). World3 is a globally aggregated systems dynamics model broken into 5 sectors: population, capital, agriculture, nonrenewable resources, and persistent pollution and containing 16 state variables (i.e., population, capital, pollution, and arable land), 100 variables total and 80 fixed parameters (Table 1; Meadows et al. 1974). The latest versions are written in STELLA and are easily runnable on a PC; however, they are not freely available to the public.

Because of the influence of the original book (several million copies were sold), this model has been the topic of intense scrutiny, debate, misunderstanding, and, one could argue, willful misinformation over the years (cf. Meadows, this volume). One interesting bit of misinformation that has been persistently circulating is the idea that the model's "predictions" have been proven totally wrong by subsequent events (*Economist* 1997) In fact, the model's forecasts made in 1972 have been pretty much on target so far[1]. The model's forecasts of collapse under certain scenarios did not start to occur until well past the year 2000. The true tests of this model's forecasts will arrive in the coming decades or so.

World3 has been criticized on methodological grounds (e.g., Cole et al. 1973). The most often cited difficulties are that it does not include prices explicitly, that it *assumes* resources are ultimately limited, and that it does not present estimates of the statistical uncertainty on its parameters. If fact, World3 is a viable and effective method to reveal the implications of the primary assumptions about the nature of the world that went into it. That is all that can be claimed for *any* model. These assumptions or "pre-analytic visions," need to be made clear and placed in direct comparison with the corresponding assumptions of the alternatives, in this case the "unlimited growth model." As Meadows et al. (1992, 2004) have repeatedly pointed out, the essential difference in pre-analytic visions centers around the existence and role of limits: thermodynamic limits, natural resource limits, pollution absorption limits, population carrying capacity limits, and most importantly, the limits of our understanding about where these limits are and how they influence the system. The alternative unlimited growth model, derived from neo-classical economic theory (see, e.g., the DICE model below), *assumes there are no limits* that cannot be overcome by continued technological progress, while the limited growth model *assumes that there are limits,* based on thermodynamic first principles and observations of natural ecosystems. Ultimately, we do not know which pre-analytic vision is correct (they are, after all, assumptions), so we have to consider the relative costs of being wrong in each case (Costanza 2000; Costanza et al. 2000).

At the time of its initial release in 1972, World3 was at the cutting edge of computer simulation. Since then, simulation capabilities have increased dramatically, as has the availability of data to calibrate and test global models. The remaining models in this review show some of that development. Before leaving this brief discussion of World3, however, we should mention some of the things that could have been done, especially in the recently released 30 year update, but have not been. The most important of these has to do with calibration and testing. In all the books on World3, calibration of the model with historical data is downplayed. This is strange, since the model runs always start in 1900 and run for 200 years to 2100. Why not show historical data for the variables in the model for which historical data is available in order to demonstrate the model's "skill" at reproducing the past? The reason given for this is that since the model is only an approximation, one should not put too much emphasis on "precise" calibrations. We think this is ultimately a mistake, since it misses the opportunity to present quantitative tests of the model's performance — tests against which World3 would fare quite well and which would address at least some of the objections of its critics. World3 is also probably the only IGM for which a true "validation" test could be run. One could take the original forecasts made in 1972 of the period from 1972 to 2002 and compare them with the actual data from the 1972–2002 period. This has, unfortunately, not yet been done.

Finally, while the discussions of World3 often point to the limited vs. unlimited growth assumptions as a key difference with conventional economic models, they do not take the opportunity to look at the relative costs and benefits of being right or wrong in those assumptions. If one does this, one can easily see that the cost of assuming no limits and being wrong is the collapse scenarios shown by World3, while the cost of assuming limits and being wrong is only mildly constrained growth (Costanza et al. 2000). Some of the more recent models reviewed below try to elaborate on these scenarios.

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[1] In an interview with the Dutch *Volkskrant* (April 16, 2005), Meadows compares his "1972" scenarios with the outcome of the Millennium Ecosystem Assessment (Reid et al. 2005) and states that this assessment actually confirms the scenarios.

IMAGE

IMAGE (Integrated Model to Assess the Greenhouse Effect; Rotmans 1990) signaled a new development in global integrated assessment modeling. Its aim was to create a comprehensive overview of global climate change. IMAGE was one of the first models that implemented OECD's Driver-Pressure-State-Impact-Response approach (InterFutures Study Team 1979) into a global model by integrating a series of different models for each important subcomponent. The model was global in scope: it simulated the emissions from energy use and tropical deforestation and the consequent climate change in different regions. A few feedback processes, such as CO_2 fertilization, were included, mainly to calibrate the model to simulate observed atmospheric CO_2 concentrations. The only impact that was simulated was sea level rise and its consequences for the Netherlands. One of the conclusions, for example, was that the costs to deal with sea-level rise would amount to more than half a percent of the Dutch national product. Most of the model components simulated the physical system (oceans, atmosphere and C on land). Societal aspects were not strongly included. They determined emission levels, and defined the cost of impacts.

The IMAGE model was developed in the second half of the eighties at the then new Dutch Institute of Public Health and Environmental Protection (RIVM). RIVM strongly advocated such an integrated modeling approach, which led to presentations in Dutch parliament and helped to raise the awareness of Dutch policy makers to climate change. When the IPCC was established, IMAGE became one of the models that helped to scope the earliest IPCC-IS92 scenarios, which defined the input for the climate-change modeling and impact community for over a decade. Also, several mitigation scenarios have been developed and published. Scientifically, IMAGE has been instrumental in the debate on global warming potentials. Because not only CO_2 but all greenhouse gases were included in the model, along with a then state-of-the-art atmospheric chemistry model, the advantages and limitations of this concept could be easily determined.

IMAGE has been systematically scrutinized using sensitivity analysis (Rotmans 1990). As a matter of fact, automated Monte Carlo analysis was first tested on IMAGE, which led to advanced protocols for experimental design for model testing (Kleijnen et al. 1992). Such analysis resulted in the identification of important variables, which have to be determined accurately and less sensitive variables, whose value does not matter so much. This analysis helped to advance the modeling research agenda. But it also showed that variables important to stakeholders rarely were the most sensitive ones, which frustrated the actual agenda setting process. Additionally, meta-modeling was tested for IMAGE. Meta-modeling searches for simpler relationships between model input and output, so that model experiments can be executed much faster. Meta-modeling techniques proved extremely useful in the development of scenarios, especially those for systems whose futures are uncertain. This was especially required in the days when computing was much less powerful. One of the outcomes of the meta-modeling of IMAGE was that besides the expected costs of dike raising, one of the most important factors determining the impacts was the not well-known role of the Antarctic and Greenland ice sheets on sea level rise. This uncertainty is still not resolved in recent IPCC reports.

IMAGE-2

IMAGE-2 (Integrated Model to Assess the Global Environment; Alcamo et al. 1998) is a further development of IMAGE. The model was initially developed to link important scientific and policy aspects of climate change in a geographically explicit manner in order to assist decision making (Alcamo 1994). Major emphasis was put on incorporating different components of the earth system, including oceans, biosphere, atmosphere and anthroposphere (i.e., society) and all major interactions and feedbacks. Over the years the model has been developed further by incorporating more detail (e.g., water use and land degradation) and improved underlying datasets. The latest version (IMAGE 2.2) has been used intensively for supporting science-policy dialogues, which led to, for example, the so-called safe landing approaches (Alcamo and Kreileman 1996) and the scenario developments of IPCC (i.e., SRES; Nakícenovíc et al. 2000), UNEP's Global Environmental Outlook, and the Millennium Ecosystem Assessment. The extensive application of IMAGE-2 is illustrated by the fact that IMAGE-2 has been one of the very few models that has been used by all the different IPCC working groups.

IMAGE-2 is one of the most advanced integrated assessment models currently available. Its major innovative aspect was (and still is) that it simulates energy and industry related activities simultaneously with land-use activities for the same set of drivers. This creates a much greater consistency for the different scenarios. Additionally, a spatially explicit global land-use model, based on a few transparent rules, creates highly different dynamics and patterns across different continents. This approach was also a major achievement. The model was calibrated against historic atmospheric CO_2 concentrations in order to balance oceanic and terrestrial carbon pools. Historic trends in land use, energy use and industrial activities for the last decades were used to calibrate the socioeconomic models. Data for these trends are derived from large internationally available databases, compiled by institutions such as FAO, UN, IEA, and the World Bank. IMAGE-2 now includes models for demography and the world economy to provide more detail and consistency for population (e.g., mortality, fecundity, and age structures) and economic drivers (trade, labor forces, resource use, and other economic constraints). The simulations start in 1995 and run until 2100 with annual time steps. Output of the model is diverse and covers many aspects of the Earth system. Scientific publications have focused on the importance of feedback processes and impacts on ecosystems and agriculture (e.g., Leemans and Eickhout 2004). Policy oriented applications have focused on scenarios and climate protection targets (e.g., Alcamo and Kreileman 1996).

The philosophy of the IMAGE-2 group has always been to be scientifically sound in order to be accepted by the policy community that needed scientific advice and/or scenarios. This was achieved by frequently publishing in the international peer-reviewed scientific literature and by installing a scientific advisory board. The strength of IMAGE-2 was therefore its widely available documentation (two books, over 100 papers, and 4 CD-ROMs). IMAGE-2 was especially well accepted by the ecological science community. Scenarios from IMAGE-2 are now widely used by that community. Its weakness is that using the model requires a well-trained multidisciplinary team and that it has proven difficult to communicate transparently the detailed results. Some argued that the presented detail, especially on maps, provided a false impression of precision. IMAGE-2 has consequently often been condemned because too little attention was paid to uncertainty (e.g., van der Sluijs 1997). Currently, new methods using aggregated indicators are being developed to communicate results and the inherent uncertainty (e.g., Leemans and Eickhout 2004).

True validation of such a model (with such a forward looking objective) and its scenarios is only possible by observing the future. As an alternative, the IMAGE-2 team tried to set up a truly independent validation exercise by starting the model in 1900 and simulating the twentieth century. The first step of this validation exercise was to develop a historic database of all relevant drivers. The resulting HYDE database (documented in Klein Goldewijk [2000] and de Vries and Goudsblom 2002) would then be used to initialize the model, after which trends and results would be compared with known trends and outcomes. The match was perfect, which created suspicion. A major problem of this validation exercise was the actual coverage of the data. Before the Second World War much of the agricultural sector was already covered in global summary statistical databases but much of forestry and energy data were still part of an informal economy and only little data with adequate coverage was available. In HYDE gaps were filed with backward extrapolation of recent trends, model-based reconstructions based on models similar to those used in IMAGE-2, etc. Other available long-term global historic databases involve similar problems. The validation exercise was thus not independent at all and had little scientific significance. IHOPE could become one of the major activities that will correct this problem.

IFs

Barry Hughes developed the International Futures simulator (IFs) inspired by the following world models: the Mesarovic-Pestel or World Integrated Model (Mesarovic and Pestel 1974; Hughes 1980), the Leontief World Model (Leontief et al. 1977), the Bariloche Foundation's world model (Herrera et al. 1976), and the Systems Analysis Research Unit Model (SARU 1978). Originally developed for educational purposes, more recently IFs' main function has been that of a policy tool. The International Futures model is used by the National Intelligence Council Project 2020, which aims to provide U.S. policymakers with future world developments which should inform policy decisions (http://www.cia.gov/nic/NIC_2020_project.html). It is also being employed in developing and analyzing scenarios for the UNEP GEO-4 report (in conjunction with IMAGE-2 and several other thematic models) and has been used to assess explicitly the attainment of the Millennium Development Goals (MDGs) outlined by the UNDP in 2004.

IFs is a global modeling system based on a data base derived for 182 countries since 1960. The model simulates onward starting at the initial year 2000 (Hughes 1996; Hughes et al. 2004). The model focuses on capturing trends in the next 10–20 years, although projections out to 2300 are produced for some audiences. Components of the model include a population module, an economic module, an agricultural module, an energy module, a social and international political module, an environmental module, and a technical module. The population module follows 22 age-sex cohorts to old age with cohort-specific fertility and mortality rates of households in response to income and income distribution to simulate average life expectancy at birth, literacy rate, and overall measures of human development (HDI) and physical quality of life. The population model represents migration among the countries and shows the effects of HIV/AIDS. A recent development includes a submodel of formal education.

The economic module is a general equilibrium-seeking algorithm based on a Cobb-Douglas production function that represents the economy in six sectors: agriculture, materials, energy, industry, services, and technology. It computes and uses input-output matrices that change dynamically with development level. The simulations account for changing consumption patterns and international trade. The model uses a social accounting matrix envelope to tie economic production and consumption to financial flows.

The agricultural model is a partial equilibrium model that represents production, consumption and trade of crops and meat, ocean fish catch and aquaculture. This model maintains land use in crop, grazing, forest, urban, and "other" categories dependant on the demand for food, livestock feed, and industrial use of agricultural products.

The energy module is a partial equilibrium module to consider known reserves, consumption and trade of oil, gas, coal, nuclear, hydroelectric, and other renewable energy forms. It portrays changing capital costs of each energy type with technological change as well as with draw-downs of resources.

The political module includes national and international politics. The national politics module computes fiscal policy, 6 categories of government spending: military, health, education, R&D, foreign aid, and a residual, and computes changes in social conditions, attitudes and the social organization. The national politics modules allows for the evolution of democracy and prospects for state failures. The international political module traces changes in power balances across states and region.

The environmental module tracks the remaining resources of fossil fuels, area of forested land, of water usage, and atmospheric carbon dioxide emissions.

Technology solutions are distributed throughout the model and represent the assumptions about rates of technological advance in agriculture, energy, and the broader economy. Technological advances are tied to the extent of electronic networking of individuals in societies and are dependant on the governmental spending model with respect to research and development.

The IFs model has undergone some historic calibration; however, the results are not easily available. Because the relationships driving the model are derived from historic data, the developers of IFs have instead focused on comparative analyses with multiple other model forecasts (Hughes 2004) in each of the issue areas captured by the model. Validation of the model proved difficult in the late 1980s (Liverman 1987). Since then, model assumptions, structure, and resolution have been improved. A similar validation exercise would be useful in demonstrating the suitability of the IFs model for global simulation.

The International Futures model has the most sophisticated and user-friendly GUI of all the models explored. It has recently been launched on the world wide web so that users can run scenarios over the internet and instantly generate output graphs and comparisons between scenarios either globally or for selected countries. IFs represents the most highly articulated socioeconomic model in our collection of IGMs, but its natural systems components are rather bare bones. It treats nature as resource sources and sinks, but with no articulation of the internal dynamics of the natural system.

DICE

The Dynamic Integrated Climate and the Economy (DICE) model (Nordhaus 1994) was developed in the early 1990s to investigate the economics of climate change. DICE is the simplest of the models evaluated in this review. The only biophysical process incorporated in the model is a very simple treatment of climate change. The optimization approach in this model is distinctly different from the systems approach taken in most of the other models considered in this review.

Quoting from Nordhaus (1994): "The basic approach of the DICE model is to use a Ramsey model of optimal economic growth with certain adjustments and to calculate the optimal path for both capital accumulation and GHG-emissions reductions" (p. 5). This was done by incorporating a greatly simplified depiction of the global atmosphere to form a set of climate-emissions-damage equations. While the simplified climate equations might pick up the major features of the emissions-climate link, the link in the model between climate change and economic impact on human and natural systems is by far the weakest one. To pick this up, the DICE model assumes a very simple relationship between global mean temperature (as a proxy for climate change) and damage: $D(t)/Q(t) = .00144\ T(t)^2$, where D is the loss of global output, Q is global output, and T is global mean temperature, all at time t (Nordhaus 1994, eq. 2.11, p. 18). The missing links are the actual feedbacks between climate change (including the more important features of precipitation change and especially the geographic distribution of changes) and ecosystem changes, and between ecosystem changes and economic performance. These links are complex, yet they are the essence of the problem being addressed. While integrated climate–economy–ecosystem models are still relatively rare (Parson and Fisher-Vanden 1995), there are several others (see above and below) which do a fairly elaborate, spatially explicit, job of estimating the climate–ecosystem linkages, and the results are anything but simple. This is why we ranked the "degree of human–natural system integration" in DICE as "low" in Table 1.

As Nordhaus (1973) has himself pointed out, any model is only as good as the assumptions that go into it. In the case of the DICE model, a thorough job has been done in analyzing the model's sensitivity to uncertainty about the parameters, but no effort went into analyzing sensitivity to some of the more basic, and more important, assumptions. The Ramsey model of optimal economic growth used as the basis for DICE *assumes* that economic growth is not limited by natural resources or environmental changes. Economic output in DICE is estimated using a production function which includes only reproducible capital, labor, and technology in its arguments. Population growth and technological change are exogenous and natural capital is completely missing. These are rather strong assumptions, given that one of the purposes of the DICE model is to integrate economic models with the rest of the natural world. In DICE, the economy goes on its merry way with no real *feedback* from the natural world. There is only the one-way flow of impacts on climate, and only through that on agriculture and ecosystems. Other work on an economic growth model with natural resources in the production function and endogenous population growth shows some very different results (Brown and Roughgarden 1995), so we can assume that adopting something other than the standard neoclassical growth model would make a big difference to the conclusions.

In addition, both the spatial and temporal resolution of the DICE model are very low, given the problem at hand. DICE is globally averaged and uses a time step of 10 years. Given that most of the underlying relationships are probably highly nonlinear and spatially discontinuous, this level of aggregation has got to cause some serious problems. As Nordhaus has himself pointed out elsewhere: "The main result of aggregation theory is that aggregation is generally possible only when the underlying micro relations are linear" (Nordhaus 1973, p. 1160). This, combined with the simple basic structure of DICE, means that there are no real possibilities for "surprises" in DICE like the kind we have come to expect in the real world, and that can emerge from some of the other models reviewed here. Yet, there is no discussion of the possibly huge impacts of aggregation error other than Nordhaus's contention that the level of aggregation used was necessary in order that "the theoretical model is transparent and the optimization model is empirically tractable." Good goals, but hardly justification for a model intended to be used to set realistic global policies on greenhouse warming. Some of these critiques have been addressed in RICE, a recent extension of the DICE model. RICE improves spatial resolution by modeling 6–10 regions separately (Nordhaus 1973; Nordhaus and Yang 1995). Further improvements on the model, including an assessment of uncertainty, are currently under development in another version called PRICE.

Finally, DICE assumes that consumption equals welfare: "We assume that the purpose of our policies is to improve the living standards or consumption of humans now and in the future." (pp. 10). This is one purpose, but consumption is not always correlated with overall human well-being or welfare, more broadly defined (e.g., Easterlin 1974, 2003; Daly and Cobb 1989; Ekins and Max-Neef 1992). There is some attempt to broaden the concept of consumption beyond conventional GNP by stating that consumption "includes not only traditional market purchases of goods and services like food and shelter but also nonmarket items such as leisure, cultural amenities, and enjoyment of the environment" (p. 10). After saying this, these nontraditional components are quickly forgotten, and the productive values of natural capital (which are probably more important) are never even considered. The problem is that material growth in the economy can become "anti-economic" if the many uncounted costs of additional growth begin to outweigh the counted benefits (Daly and Cobb 1989). The DICE model, through its simple damage function, includes only a very crude estimate of some of these costs, but it has no way of picking up any nonconsumption welfare effects or feedback effects from the environment to the economy. Yet Nordhaus blithely talks about the "welfare" effects of various policy scenarios. What DICE actually models is (at best) the marketed, and some small piece of the nonmarketed, consumption effects, and these may in fact be opposite to the true welfare effects as the planet's natural capital base continues to erode.

TARGETS

Targets (Tool to Assess Regional and Global Environmental and heath Targets for Sustainability; Rotmans and de Vries 1997) is also a direct descendent of IMAGE. It aimed to redirect and accelerate the discussions from climate change towards global change. Its main innovation was that the model assumed that changes in drivers were a direct function of different perspectives on how the world system functions and is managed. The drivers thus do not define boundary conditions but are an integral part of the model itself. A future, as defined by TARGETS, provides the different implications of such a perspective in terms of population and health, energy, use of land and water, and biogeochemical cycles. Another new aspect is not to list the absolute impacts but indicate them in terms of risks for unsustainable developments.

The model is thus strongly based on the concept of cultural perspectives to deal with the apparent uncertainty in the interactions between humans and their natural environment (van Asselt and Rotmans 2002). The natural and socioeconomic dimensions are highly integrated in TARGETS. As such it has departed from the simpler causal chain or DPSIR (Driver-Pressure-State Change-Impact-Response) models as used earlier. TARGETS is based on the basic notion that in the absence of complete knowledge and in order to guide choices and actions, people use stylized and simplified images of the world around them. These images are based on experiential trends interpreted by implicit rules. This complex represents human values and beliefs. These images further form the bases of different world views and also determine the behavior of people and thus their interactions in the Earth system.

TARGETS consists of five submodels: population and health, energy, land and food, and water. Each of those submodels is a DPSIR model but they are linked through a socioeconomic scenario generator, in which policy responses are explicitly incorporated. All submodels can be used in a stand-alone mode as well, in order to allow model and data comparisons, comparisons with other models, and targeted validation and sensitivity analysis. The TARGETS team further argues that having adequate insight in the behavior of the submodels helps to understand the behavior of the interactions in the full model as well. The level of and approach towards integration achieved in TARGETS could well be an example for IGMs to be developed in IHOPE.

The TARGETS approach does not provide simple answers and again stresses that the future is highly uncertain. It generates insights in the accelerating influence of the human race and as such strongly supports the notion of the Anthopocene (Crutzen and Steffen 2003). It also provides a new insight (not appreciated by many modelers) that individual people perceive changes in their environment differently, which influences the rationale for selecting appropriate responses. TARGETS is not used to develop scenarios, but utopias: Worlds dominated by a particular world view or perspective. Although innovative and challenging, the stakeholders evaluating the model results had large difficulties in understanding the role of all these perspectives (see, e.g., the Ulysses project: http://zit1.zit.tu-darmstadt.de/ulysses). Additionally, the lack of spatial detail for the land, water, and biogeochemical simulations was also seen as a major drawback. TARGETS, however, was quite influential in setting the stage for the acceptance of the narrative scenarios approach, later also adopted by the IPCC SRES scenarios (Nakícenovíc et al. 2000) and by the Millennium Ecosystem Assessment.

GUMBO

The Global Unified Metamodel of the BiOsphere (GUMBO; Boumans et al. 2002) was developed as part of a working group at the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, CA. Its goal was to simulate the integrated earth system and assess the dynamics and values of ecosystem services. It is a "metamodel" in that it represents a synthesis and a simplification of several existing dynamic global models in both the natural and social sciences at an intermediate level of complexity. The current version of the model contains 234 state variables, 930 variables total, and 1715 parameters (Table 1). GUMBO is the first global model to include the dynamic feedbacks among human technology, economic production and welfare, and ecosystem goods and services within the dynamic earth system. We rated its degree of human–natural system integration as "high" in Table 1. GUMBO includes five distinct modules or "spheres": the Atmosphere, Lithosphere, Hydrosphere, Biosphere, and Anthroposphere. The Earth's surface is further divided into eleven biomes or ecosystem types, which encompass the entire surface area of the planet: *Open Ocean*, *Coastal Ocean*, *Forests*, *Grasslands*, *Wetlands*, *Lakes/Rivers*, *Deserts*, *Tundra*, *Ice/rock*, *Croplands*, and *Urban*. The relative areas of each biome change in response to urban and rural population growth, Gross World Product (GWP), and changes in global temperature. Among the spheres and biomes, there are exchanges of energy, carbon, nutrients, water and mineral matter. In GUMBO, ecosystem services are aggregated to 7 major types, while ecosystem goods are aggregated into 4 major types. Ecosystem services, in contrast to ecosystem goods, cannot accumulate or be used at a specified rate of depletion. Ecosystem services include: soil formation, gas regulation, climate regulation, nutrient cycling, disturbance regulation, recreation and culture, and waste assimilation. Ecosystem goods include: water, harvested organic matter, mined ores, and extracted fossil fuel. These 11 goods and services represent the output from natural capital, which combines with built capital, human capital, and social capital to produce economic goods and services and social welfare. The model calculates the marginal product of ecosystem services in both the production and welfare functions as estimates of the prices of each service.

Historical calibrations from 1900 to 2000 for 14 key variables for which quantitative time series data was available produced an average R^2 of 0.922. A range of future scenarios to the year 2100 representing different assumptions about future technological change, investment strategies and other factors have been simulated. The scenarios include a base case (using the "best fit" values of the model parameters over the historical period) and four initial alternative scenarios. These four alternatives are the result of two variations (a technologically optimistic and skeptical set) concerning assumptions about key parameters in the model, arrayed against two variations (a technologically optimistic and skeptical set) of policy settings concerning the rates of investment in the four types of capital (natural, social, human, and built). They correspond to the four scenarios laid out in Costanza (2000), and are very similar to the four scenarios used in the recent Millennium Ecosystem Assessment.

While this is an early version of GUMBO, some preliminary results and conclusions include:

- A high level of dynamic integration between the biophysical earth system and the human socioeconomic system is important if we are to develop integrated models with predictive capabilities. The IHOPE project will be extremely important in fostering better integration.
- Preliminary calibration results across a broad range of variables show very good agreement with historical data. This builds confidence in the GUMBO model and also constrains future scenarios. The model produced a range of scenarios that represent reasonable rates of change of key parameters and investment policies, and these bracketed a range of future possibilities that can serve as a basis for further discussions, assessments, and improvements. Any user can change these parameters further and observe the results.
- Assessing global sustainability can only be done using a dynamic integrated model. However, one is still left with decisions about *what* to sustain (i.e., GWP, welfare, welfare per capita, etc.). GUMBO allows these decisions to be made explicitly and in the context of the complex world system. It allows both desirable and sustainable futures to be examined.
- Ecosystem services are an important link between the biophysical functioning of the earth system and the provision of sustainable human welfare. We have found that their physical and value dynamics are quite complex.
- The overall value of ecosystem services, in terms of their relative contribution to both the production and welfare functions, is shown to be significantly higher than GWP (4.5 times in this preliminary version of the model).

- "Technologically skeptical" investment policies are shown to have the best chance (given uncertainty about key parameters) of achieving high and sustainable welfare per capita. This means increased relative rates of investment in knowledge, social capital, and natural capital, and reduced relative rates of consumption and investment in built capital.

The GUMBO model is available over the internet but requires the Stella software for the user to run. The GUI developed for GUMBO is built into the Stella software, but does not come with instructions or guidance.

Model Intercomparisons

The natural and social processes important to capture in IGMs include human demographics and development, economic production in multiple sectors (energy, food production, industry, and forestry) and the response of the atmospheric, terrestrial, and aquatic ecosystems to increasing degradation. Perhaps the most challenging component of an integrated global model is linking these impacts on ecosystem health back to human demographics and economic projections (Figure 1). In so doing, we must pay especially good attention to issues of spatial and temporal scale. The models considered in this chapter range in complexity, spatial aggregation (from globally aggregated models to highly spatially explicit models), and temporal resolution (decadal vs. annual time steps).

We have attempted a concise comparison of model resolution, complexity, feedback, and empiricism. Table 1 summarizes the time step, spatial and temporal resolution, and the degree of human–natural system integration found in each model. Model complexity and empiricism is captured in Figure 1, which gives a quick graphic overview of the relative coverage and complexity of each model. Model components included as exogenous inputs are given a rank of 1. For example, most of the IGMs use policy scenarios as an exogenous input. Model components that are calculated endogenously but are not included in feedbacks to other model components were assigned a rank of 2. For example, the IMAGE model calculates sea level rise in the water cycle but this variable does not feed back into other model variables. Endogenous model components that are included in inter-compartmental dynamics are ranked 3 and 4 depending on the level of internal complexity captured and spatial scale. For example, the GUMBO model is a globally aggregated meta-model which was given a rank of 3 for most endogenous feedback components. Table 2 documents the justification for each of the model component rankings. A gray-scale ramp has been included to illustrate the relative level of historic model calibration.

Conclusions: IHOPE and IGMs

IHOPE can benefit from explicit connections with IGMs and the IHOPE project can spur significant advances in IGMs through several mechanisms, including the following:

- **Allowing much more elaborate quantitative calibration and testing of IGMs.** IHOPE's data bases will be a shared community resource that will be extremely useful for this purpose. We might consider the implementation of an *evolutionary selection cycle* among models of humans in nature, whereby the IHOPE project would oversee the testing of alternative models against the common data base and rewarding of the most successful models to encourage their further development.
- **Extending the temporal extent of IGMs outside the decadal time scale**. This will also be extremely important for calibration and testing, since the period 1900-present has been one of steady exponential growth in most human system variables. One needs to go further in the past

to observe societal collapses (Diamond 2004). Forecasting these collapses (and lack of collapses) will be an important way of testing the skill of integrated models.

- **Spurring a much higher degree of human and natural system integration in model structure.** By assembling integrated teams of researchers from across the natural and social sciences and the humanities to assemble an integrated data base, IHOPE will build bridges that will also allow more integrated thinking about model construction and testing.

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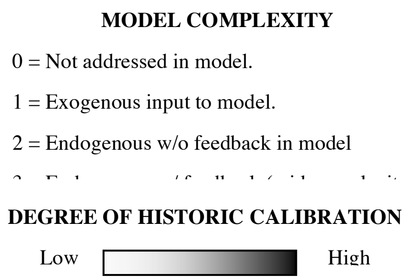
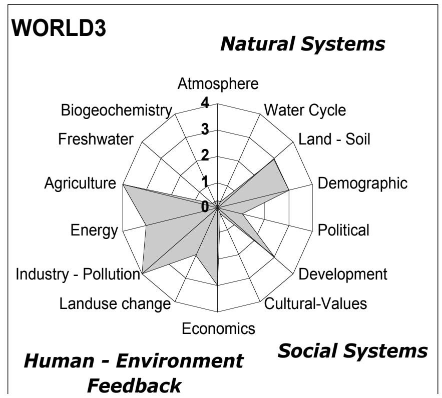
WM Iintegrated Vorld Model)	Kile and Rabehl 1980	a.gatech.edu /peter/iwm.html		1 year	Global		24 regions			Moderate	Low
MAGE (Integrated Aodel for the Assessment of the Greenhouse effect)	Rotmans 1990		1900-2100	0.5 years	Global (impacts only for The Netherlands)	7 ecosystems	9 regions	Human emissions , Atmosphere, biosphere & oceans	many	Low	Low
Integrated Model or the Assessment of the Global Environment)	Alcamo 1994 Alcamo, Leemans & Kreileman	sin.org/datasets/rivm/image2.0-home.html	1900-2100	1-5 year	Global	.5 degree grid	17 regions	Economy, Society, Atmosphere, biosphere & oceans	moderate (but replicated in each grid cell)	Moderate	Medium
Fs (International Futures Simulation)	Huges 1996	http://www.du.edu/~bhughes/ifs.html	1960-2100	1 year	Global	182 countries	182 countries	economy		Moderate	Medium
DICE (Dynamic Integrated Model of Climate and the Economy)	Nordhaus 1992, 1994	http://sedac.iesin.org/mva/DICE/DICEHP.html	1990-2100	10 years	Global	Globally Aggregated	Globally Aggregated	Economy, climate	very few	Low	Medium-High
TARGETS (Tool to Assess Regional and Global Environmental and health Targets for Sustainability)	Rotmans and de Vries 199	http://sedac.iesin.org/mva/iamcc.tg/TGsec4-2-7.htm	1900-2100	1 year	Global	Globally Aggregated	4 regions	Economy, Society, Atmosphere, biosphere & oceans	many	Moderate	Medium
GUMBO (Global Unified Metamodel of the Biosphere)	Boumans et al. 2002	http://www.um.edu/giee/GUMBO/	1900-2100	1 year	Global	11 biomes	Globally Aggregated	Anthroposhpere (Economy - Human, Built, Social capital), Atmosphere, Biosphere, Hydrosphere, Lithosphere,	moderate	High	Medium-High

The classes for the variables correspond to: 'very few' up to 10, 'few' up to 100; 'moderate' up to 1000, 'many' upto 10000 and 'very many' more than 10000. Only the var
The unit model would be replicated in each c

Figure 1. Diagram of complexity with which IGMs capture socioeconomic systems, natural systems, and human-environment feedbacks





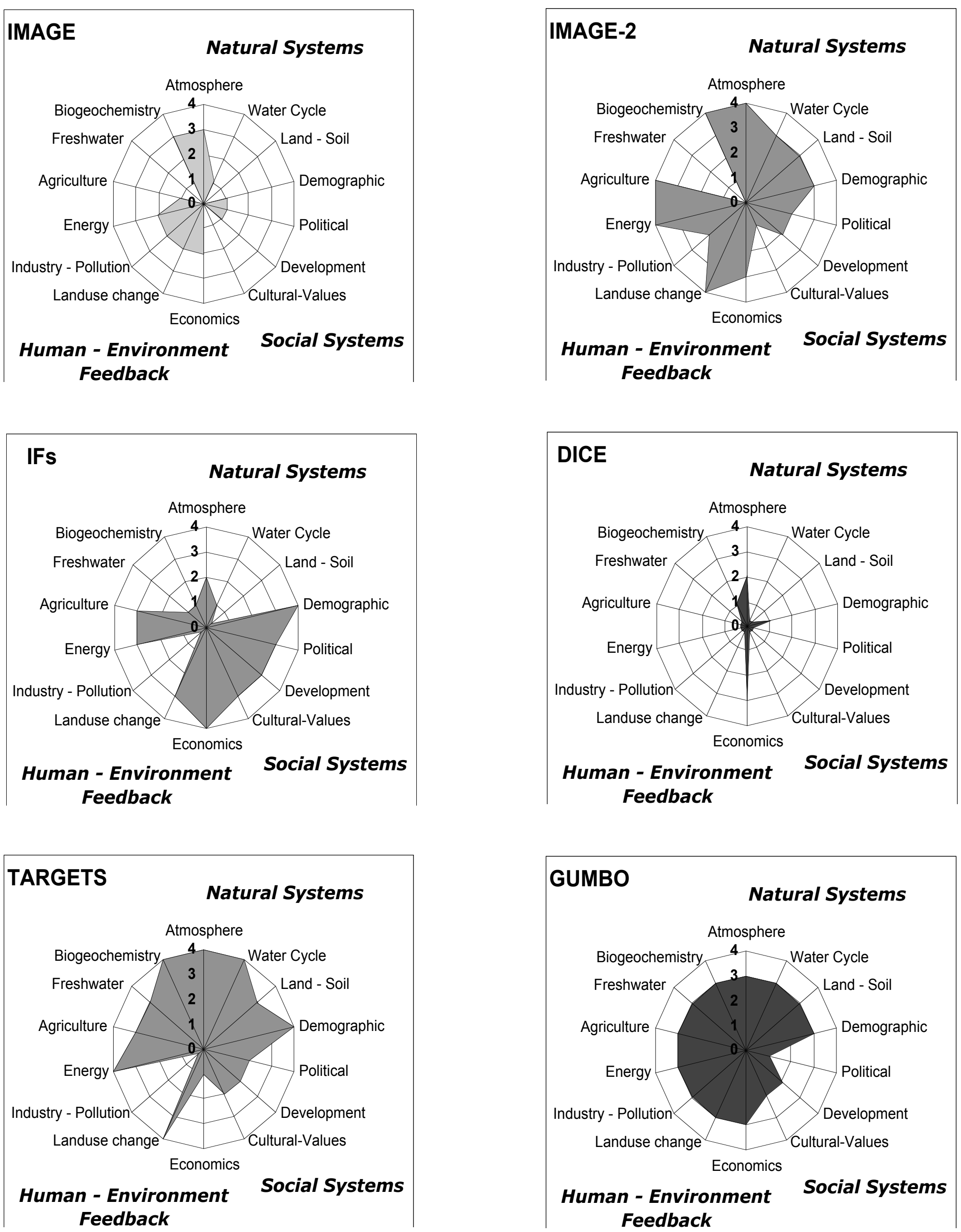


Table 2. Documentation of complexity with which IGMs capture socioeconomic systems, natural systems, and human-environment feedbacks

	WORLD3	IMAGE	IMAGE-2	Ifs	DICE	TARGETS	GUMBO
Atmosphere	None.	CO2, climate change feedback.	CO2 endogenous, climate change feedback.	CO2 endogenous. No feedback.	Exogenous.	Six energy-related gases calculated. Feedback.	Carbon, water, nutrient cycles.
Water Cycle	None.	Sea level rise calculated.	Sea level rise calculated.	Exogenous.	None.	Tracks 10 water reservoirs (surface, ground, soil, and ocean).	Calculates surface, ground, soil, and ocean water stocks.
Land - Soil	Land erosion, fertility.	None	None	None.	None.	Erosion.	Weathering, erosion, fertility.
Demographic	Feedbacks from all other modules.	Exogenous.	Demographic module.	Complex population predictions.	Exogenous.	Population and health submodel w/ feedback.	Total population (urban and rural) w/ feedback.
Political	Scenario inputs.	Scenario inputs.	Scenario inputs.	Predicts govn. spending by sector, democracy & state failure.	None.	Scenario inputs.	Scenario inputs.
Development	Simple.	None.	None.	Predicts Human Development Index and Millennium Development Goals.	None.	Development indices predicted.	Calculates Sustainable Social Welfare and human capital.
Cultural-Values	None.	None.	None.	Predicts value change between traditional/secular-rationalism to survival/self-expression.	None.	Driver of responses modules.	Technological optimist v. technological skeptic.
Economics	Industry, service, agricultural output.	Calculates impacts of climate change. No feedback.	Calculates impacts of climate change. No feedback.	Complex dynamics by sector.	Damage costs calculated. Feedback to other economic components.	Economic scenarios drive model.	Calculates built capital and ecosystem goods and services.
Landuse change	Agriculture/ Industry	Agriculture/ Forest	Spatially explicit global landuse module.	Urban/Forest/ Agriculture	None.	Forest/Grass/ Agriculture	Forest/Wetland/ Grass/Urban/ Desert.
Industry - Pollution	Endogenous w/ feedback.	Exogenous	Exogenous	None.	None.	None.	Waste calculated from built capital.
Energy	Incorporated into non-renewable resource sector.	Calculates change in energy use. No feedback.	Calculates change in energy use. No feedback.	Energy demand & fossil fuel reserves computed. Feedback with economic sector.	None.	Demand for five sectors and energy supply. Feedback.	Calculates energy use and proportion from fossil fuels. Feedback.
Agricultural	Driven by food per capita & landuse change	Simple. No feedback.	Simple endogenous. No feedback.	Production driven by population. Feedback to landuse and economics.	None.	Food demand driven by population and economics.	Calculates agricultural impacts. Feedback to economics.
Freshwater	None.	None.	Calculates water use.	Calculates water demand but not availability.	None.	Water demand and availability calculated. Feedbacks.	Calculates water demand and availability. Feedback to economics.