Modeling Human Dimensions of Global Environmental Change

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Modeling Human Dimensions of Global Environmental Change

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The history of humankind is a continuing record of interactions between people's efforts to improve their well being and the environment's ability to sustain these endeavors. Environmental constraints have led to innovations and social development, as well as social stagnation and human suffering. While the interactions throughout most of history were on a local scale, during the last decades awareness has grown so that the complexity and increasing scale of the interactions are demanding new forms of environmental management. New threats to mankind emerge, such as climate change, acid rain, ozone depletion, resource exhaustion, reduction of biodiversity, and limits to the availability of food and unpolluted fresh water. In fact, the globe is changing rapidly due to human activities, and humankind is, and will increasingly be, suffering from global environmental change.

One response from the scientific community to understand the relations between human activities and the environment is the use of modeling, that is, constructing formal descriptions of natural and societal change and their mutual interactions. Although making accurate predictions for long term future developments is inherently impossible, models can help us to show the interdependence of various activities and consequences in time and space. In that way, models can be used to communicate information and insights from the scientific community to policy makers and other stakeholders.

A number of fundamental issues in modeling the human dimensions of global environmental change are discussed. These dimensions relate to the interactions between humankind and the global ecosystem. How do human activities change our environment, how are humans affected by changes in our environment, and how does humankind respond to these changes? This contribution focuses on the behavior of humans in relation to their environment. Moreover, two fundamental related issues are discussed:

- *Given our limited knowledge of reality, we have to make all kinds of subjective assumptions about the functioning of human and natural systems in order to make decisions. How can models be of help for decision-making when subjectivity is unavoidable in developing models?*
- *On the macro-scale, phenomena are observed which are the result of actions of agents on lower levels such as of households, firms, organizations and nations. How can we explore future developments of these macro-scale phenomena?*

Although there is an increased use of modeling human dimensions of global environmental change, these issues are not well captured in current mainstream modeling practices. These issues are discussed in the context of developments in modeling human dimensions during the last 30 years and address promising developments for the future.

There are many kinds of models. A general classification is the distinction between formal mathematical models and non-formal models such as stories and cartoons. Sometimes people are role models of how one might live, such as Nelson Mandela or Claudia Schiffer. Only the formal models are dealt with here. The advantage of these formal models is that they are explicit and many of them are computer models that can be used to do repeated experiments.

Formal models are used in science very frequently, especially since the seminal work of Isaac Newton, more than 300 years ago. Formal models were mainly used to describe natural systems, such as calculating the trajectories of cannon balls or celestial bodies. Due to the success of these models, mathematical models were increasingly used in social science, especially in economics. However, human beings are not similar to cannon balls. Human beings can decide to obey traffic laws, but cannon balls cannot decide to obey the law of gravity.

The application of models from physics to social phenomena is problematic, but is still widely used. This article addresses new ways of modeling social phenomena by using multi-agent modeling to simulate interactions between agents, which are behavioral entities such as persons, households and firms. But first the field of modeling human dimensions of global environmental change is discussed.

Currently, models are widely used to describe the relations between human activities and the environment. Moreover, these models have often played a central role in setting environmental problems on the policy agenda, by exploring the consequences of alternative scenarios and by designing acceptable solutions for managing environmental problems. An example of an environmental problem for which the use of models is central is climate change. The possibility of human induced climate change is actually a policy problem that was put on the agenda after alarming model-based studies. Svante Arrhenius estimated at the end of the 19th century the consequences of a doubling of atmospheric carbon dioxide on the global mean temperature to be about 3 °C. Since the late 1950s, atmospheric carbon dioxide has been measured systematically, and currently the level is about 30% higher than pre-industrial levels. During the last 30 years, more detailed climate system models have been developed, and the results are compared with the increasing amount of (satellite) data. Still, these models are not able to describe observed climate accurately on a detailed spatial level. Besides increased efforts in modeling the climate systems, models of the human dimensions of climate change have been developed. These models were used to speculate on the possible consequences of climate change on economic growth, agricultural production and human health. Furthermore, models were developed to estimate the costs of mitigating so-called greenhouse gases. The impacts of climate change on various social and ecological factors are based on laboratory experiments, extrapolations from field studies, historical (regional) climate-change analogues and expert judgements. The increased insights into potential impacts of human induced climate change led to the current high position of the climate change issue on the policy agenda.

Policy decisions related to climate change are mainly determined by model outcomes. Many uncertainties, speculative assumptions and lack of information surround these outcomes. Thus, because the potential consequences of climate change as estimated by models are so severe, the precautionary principle is often advocated to reduce potential risks. Nevertheless, it is clear that the many uncertainties that surround the model outcomes have generated an intensive debate. Some scholars highlight the potential benefits of climate change on, for example, agricultural production, due to higher levels of atmospheric CO_2 and more suitable temperatures in Canada and Russia. Others argue that human induced climate change will not occur due to damping feedbacks of the biogeochemical cycles. Various scholars warn of positive feedbacks that may amplify climate change to catastrophic levels. The mainstream opinion on the size and impacts of climate change is represented by the reports of the Intergovernmental Panel on Climate Change (IPCC), an international scientific organization established in 1988 to assess scientific research on climate change. In 1995, the IPCC concluded that "the balance of evidence suggests a discernible human influence on the climate." Although science is not a democratic process, the assessments of the IPCC try to synthesize a mainstream picture of the climate change issue which can be used in the international policy process to formulate policies to reduce greenhouse gas emissions. Such an authorized synthesized picture on the problem is desired by policy makers, since they have difficulty in handling the many uncertainties and complexities of the climate change problem. The model-based analysis of the IPCC suggests objective assessment. The idea that models can create objective predictions of the future is widespread among stakeholders who deal with global environmental change. Some stakeholders who doubt this objectivity do not want to use any model analysis at all. However, the traditional view that models guarantee or suggest objectivity is outdated. Model analyses, especially related to human dimensions, are highly influenced by subjective assumptions and interpretations. The challenge is to design ways to use models in such a way that they improve our understanding of reality. Improved mental models can improve decision-making. Therefore, the model-projections itself are not the most important element of model; rather it is the modeling process and the end use of models. This debate mirrors the discussion on world models during the early 1970s.

WORLD MODELS

Integrated models addressing the human dimensions of global environmental change elaborate a tradition that was founded in the early 1970s by the Club of Rome (*see* **Club of Rome**, Volume 4). Over the past 30 years many models have been built in the tradition of system dynamics, as well as other modeling techniques. In the early days the models of the Club of Rome were criticized as being based on too few empirical data, too high an aggregation level, and too many subjective assumptions. The criticism of the earlier models still holds for many of the current modeling activities.

The models of the Club of Rome were the so-called World models. Jay Forrester developed the World 2 model during the summer of 1970 based on his system dynamics approach. According to this approach, the world can be described through a conglomeration of interacting feedback loops. The World 2 model can be considered as a first sketch of a world model, without empirically based estimation of suggested causal relations.

A larger project, led by Dennis Meadows, resulted in the World 3 model, and the influential book *Limits to Growth* (Meadows *et al.*, 1972). The World 3 model contains the

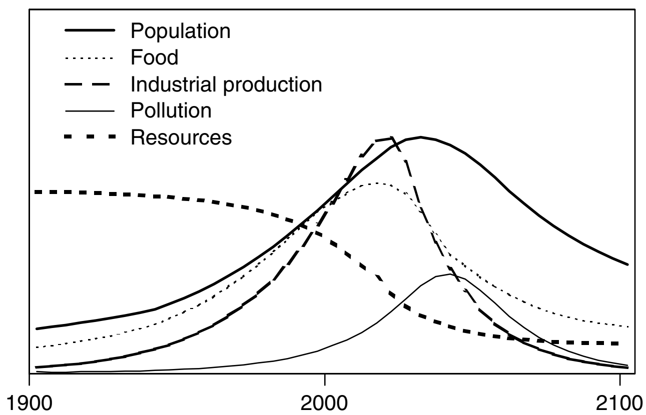

Figure 1 Standard Run of World 3. (Adapted from Meadows *et al.*, 1972)

resource sectors, population, pollution, capital and agriculture on an aggregated global level. The standard run of the World models is one of growth followed by collapse (Figure 1). The collapse occurs because of non-renewable depletion. The industrial capital stock grows to a level that requires enormous input of resources, more and more capital must be used to obtain those resources, leading to less re-investment, and finally the collapse of the industrial base. Population decreases when the death rate is driven upward by a lack of food and health services. If the resource base is assumed to be much larger, collapse happens only a few years later due to food shortages and/or high pollution levels. Although it was recognized that there are various shortcomings in the models, Meadows and his colleagues argued that the model behavior was fundamental and general, and sufficiently developed to be of some use to decision-makers.

Managing Uncertainty, Complexity and Incomplete Information

Numerous scholars have criticized the World-model studies. Economist WD Nordhaus classified the World 2 study as misleading since it was not empirically tested enough and ignored mainstream economic insights. Other scholars concluded that due to the scarcity of relevant empirical information, relationships in the world models are subjective. Given the uncertainties, other sets of equally plausible assumptions can lead to a completely different picture. In fact, the outcomes of the models are largely the mental models of the model builders.

Some of the criticism was misplaced. The model outputs were interpreted as predictions, not merely as scenarios, i.e., 'what if' futures. So, when the predictions did not come true, scientists were blamed for inaccurate doomsday forecasts. Actually, the *Limits to Growth* scenarios had a profound effect on the public and government.

Scientific criticism on the World models of 30 years ago mainly concentrate on two topics. First, subjective assumptions had to be made about model relations and parameters due to incomplete knowledge or even ignorance. This was especially important for the linkages between subsystems. Examples were the effects of pollution on health, the interaction between demographic and economic dynamics, the role of technological innovations in resource availability, and the relations between material and energy inputs and economic output. Second, the complexity of the underlying subsystems and the linkages made it questionable whether a high aggregation level can lead to meaningful and relevant interpretations and results.

These problems of subjectivity and aggregated relations are still relevant for the current use of models. Although the use of models has increased, we still have no satisfactory solutions of how to manage incomplete information and insights, large uncertainties and different scales. This is illustrated here by the characteristics of the current generation of global models.

Integrated Assessment Models of Global Change

Global modeling re-emerged during the early 1990s as integrated assessment modeling, mainly because of the importance of the global climate change problem (Janssen, 1998). Integrated assessment models try to describe quantitatively as much as possible of the cause–effect relationships and the cross-linkages and interactions between the elements of the world system. Integrated assessment models are usually composed from meta-models of various subsystems. A meta-model is a simplified, condensed version of a more complicated and detailed model, which provides approximately the same behavior as the expert model from which it is extracted.

Integrated assessment models are one of the tools in the toolkit of integrated assessment. Other tools are policy exercises, dialogues between science and policy people, data analysis, scenario analysis and expert models. Integrated assessment is therefore a broader approach aimed at helping prioritize policy-making and research activities and giving insights into uncertainties and missing links of knowledge. It is used in a process whereby knowledge from a variety of scientific disciplines is combined, interpreted and communicated, with various stakeholders such as scientists, policy makers and non-government organizations involved.

The integrated models that are used describe the whole cause–effect chain from economics, energy production, emissions, land use changes, to changes in the biogeochemical cycles, the climate system, and impacts of climate change on human activities and the environment. There is no single approach to capturing the complexity of the system as a whole. In general, two types of approaches can be considered. The first approach, *process-oriented modeling*, is rooted in natural science and simulates the consequences of economic development on energy production, land use changes, biogeochemical cycles, climate system and impacts of climate change. The models are often detailed at the spatial and temporal level. The other approach, *cost–benefit modeling*, is rooted in economics and maximizes discounted long-term welfare. Models using this second approach describe the physical consequences in less detail, but express the impacts of climate change and the efforts to reduce emissions in monetary units in order to derive an optimal response by balancing costs and benefits.

Both approaches are confronted with the same dilemmas as the World models of the early 1970s. Although much more empirical information is available, many components in models are surrounded by large uncertainties. Therefore, subjective assumptions have to be made. Also the complexity of scales remains an unsolved issue.

Besides these problems, most integrated assessment models have limited abilities to capture the broad human dimensions of climate change. The models are suitable for generating projections of economic output and the costs of climate change, but they are limited in many ways. Simple macro relations are assumed between economic activities and physical processes, but empirical insights are conflicting. Current (economic) models focus on utility of consumption as the driving force of human behavior, although it is questionable how this is related to the quality of life. There is limited insight into the physical dimension of satisfying human needs, but this understanding is needed before something plausible can be said about decoupling economic development and environmental pressure. Current integrated models include only the free market as an institution, although there are many other forms of economic organization and institutions.

One of the reasons for the limitations of the current generation of integrated models is the use of a rather mechanistic modeling paradigm, which is not able to include novelty, evolution and surprise. The role of modeling paradigms is now discussed in more detail.

MODELING PARADIGMS

A lot of controversies among modeling studies are caused by the difference in modeling approach that is adopted by the various scientists. Each modeling approach, or in a broader context, each modeling paradigm, involves its own set of theories, concepts, mathematical techniques, and accepted procedures for constructing and testing models. We can distinguish between deterministic and stochastic models, simulation and optimization models, reductionistic and integrated models, linear and non-linear models, one-agent and multi-agent models, and so on. Instead of discussing all kinds of possible paradigms, the difference between the reductionistic Newtonian approach and the complex adaptive systems approach is examined. This illustrates the transition in science that is currently occurring and explains fundamental differences on how to use models for assessing the future.

Mathematical modeling has long been influenced by physical science, which has developed a mechanistic, reversible, reductionistic and equilibrium-based explanation of the world. This proved to be very successful in calculating trajectories of moving objects (e.g., cannon balls) and predicting the positions of celestial bodies. The work of Isaac Newton, culminating in the *Principia Mathematica Philophiae Naturalis* in the late 17th century, was, and still is, very influential. The associated rational and mathematical way of describing the world around us was also applied in the social sciences, economics and biology. Despite the fact that later developments in the natural sciences seriously constrained the applicability of the mechanistic paradigm, its relative simplicity had a great appeal to scientists from various disciplines working with models. However, despite the widespread use of this approach, the mechanistic paradigm is increasingly criticized. The foundations of the mechanistic view: reversibility, reductionistic, equilibrium-based and controllable experiments, have faded away in the light of a number of new scientific insights.

First, the discovery of the Second Law of Thermodynamics brought down the notion of reversibility. The Second Law states that the entropy of a closed system is increasing. This means that heat flows from hot to cold, so that less useful energy remains. One of the consequences of the Second Law is the irreversibility of system behavior and the single direction of time. Changes within systems cannot reverse back just like that (irreversible). This is in contrast to many mechanistic models, in which time can easily be reversed to calculate previous conditions.

Second, the equilibrium view of species was brought down by Charles Darwin's book on the origin of species during the middle of the 19th century. The static concept of unchanging species was replaced by a dynamic concept of evolution by natural selection and adaptation of species, thereby fundamentally changing our view of nature. Natural systems are in continuous disequilibrium, being interdependent and constantly adapting to changing circumstances.

Third, the theories of quantum mechanics have confronted us with a fundamental uncertainty regarding knowledge about systems, especially on the level of atoms and particles. The uncertainty principle of Heisenberg is well known, stating that it is impossible to simultaneously measure the position in space and momentum (mass times velocity) of any particle. The statement by Laplace in the early 19th century that if every position of every atom was known, the future might be predicted exactly, became therefore a lost illusion. Moreover, the notion of fundamental uncertainty implied that fully controlled experiments are strictly speaking not possible.

Notwithstanding the fact that these developments in the natural sciences changed our perception of the world, (mathematical) models are still mainly based on a mechanistic view of systems. For example, current mainstream economics is based on its success during the period after the Second World War, which was characterized by stable economic growth. Technology could seemingly handle any difficulty that came along. Affluence was seen as growing and permanent, and the standard of living, it was believed, would continue to improve for individuals and generations. The world economy was a place of simple equilibria and linear responses. Cost–benefit analysis, optimization and econometric models seemed to be quite appropriate.

Since the 1970s, various events have made us aware of the non-linearity of economic systems. The oil crisis ended unlimited economic growth, the Berlin wall collapsed in 1989, the Asian financial crisis at the end of the 1990s, the various crises on the stock markets, and so on. The economic system seems to be characterized by unstable states, non-linear responses and unpredictability. Still, mainstream economics uses its successful tools of the early days, probably because of their analytical power; certainly not because of their ability to explain reality. Increasing numbers of economists are trying new tools to explain the observed behavior of economic systems. This has led to the study of non-linear dynamics and evolutionary processes as emerging fields in economics although not always accepted by mainstream economists. This new type of economics studies the formation of patterns, evolution of economic systems, endogenous technologies, and so on. Furthermore, next to analytical tools, this new field of economics uses computers as a kind of laboratory to test hypotheses.

The emergence of new ways of studying the world around us has also emerged in other disciplines where studies are made of the origins of order, self-organization, emergence of structures, adaptation of agents in a changing environment, and many more new ideas. The general focus of this new modeling paradigm is to study how systems change and organize their components to adapt themselves to the problems posed by their surroundings. Examples of these systems are economies, ecosystems, immune and nervous systems, organisms and societies.

Although various scholars long ago discussed the importance of studying the evolution of systems, the rapid developments of the computer have provided scientists with a new tool in recent decades, which can be used to investigate evolution, self-organization, interactions between agents and emergence of structures on a macro scale by simple local rules. These systems can be grouped under the common name complex adaptive systems. They are studied by a number of new computation-based modeling tools, including genetic algorithms, cellular automata, neural networks, and artificial life forms.

The characteristics of these new types of tools are illustrated using one of these tools: genetic algorithms. *Genetic algorithms* have been developed to simulate the process of natural selection by considering a population of agents producing offspring who are similar, but not identical, to their parents. This process depends on three genetic operators: selection, crossover, and mutation. *Selection* means that the genetic algorithm selects n copies of the strings (genetic code) in the population by a random process that favors the most fit. Subsequently, these copies are probabilistically paired in a mating process whereby each pair produces two offspring by means of crossover and mutation. *Crossover* means that two offspring are created with a certain probability that the genetic information is crossed over; otherwise, the offspring are identical to the parents. In the case of crossover, the parent strings of genetic information are split randomly and are swapped to shape two new strings. Each element of the genetic information has a small probability of being altered. This *mutation* is independent of what happens with the other genetic information. Due to their adaptive characteristics, genetic algorithms are powerful tools for improving and finding good solutions even in complex changing environments. Moreover, genetic algorithms are based on irreversible changes, stochastic processes and evolution (*see* **Resilience**, Volume 2).

Genetic algorithms are one of the computational tools used for developing models to study complex adaptive systems, which emerged as a new field in science. Since the late 1980s, the Santa Fe Institute has provided a prime focus for exploring and deepening the insights from complex adaptive system studies and provided new opportunities for transdisciplinary studies (Waldrop, 1992). It is expected that the study of complex adaptive systems will become an important field in transdisciplinary environmental science. The Resilience Alliance is one of the first international communities to study environmental science from this new perspective. An overview of their work is given in Gunderson and Holling (2001).

Validity of Models

An important difference between the two modeling paradigms is how to use models, and how to validate models. From the viewpoint of mechanistic explanations of reality models are valid when predictions generated by the model are not rejected. An example of this Popperian type of validation is the development of an econometric model. The timeseries of data is split into two. One part is used to estimate the model and to generate predictions, and the second part to test the predictions of the constructed model. This empirical validation leads to problems according to the complex adaptive systems paradigm, which focuses on evolving structures and is often based on qualitative insights. Since small differences in initial values can lead to large output differences, models of complex adaptive systems are not suitable to generate predictions. In fact, this problem goes back to the classical three-body problem (e.g., the system involving Earth–Moon–Sun), which has been studied extensively with a variety of methods beginning with Newton. Despite the large number of studies, no complete analytic solution in closed form has been found. Furthermore, for some initial conditions this system is found to produce chaotic unpredictable behavior. This example shows that when interactions among agents are taken into account, the Newtonian approach does not work. Therefore, validation in this line of modeling is based on expert judgements and relations with theoretical insights. This type of validation can be called conceptual validation. In fact, validation is not a test, but a subjective process.

The difference between opinions on how to measure the quality of models leads also to differences in how to use models. According to the Newtonian modeling paradigm, a model that is tested empirically and is validated can be used to make accurate and objective predictions. However, according to the complex adaptive system perspective, models can only be used to study qualitative structures, and should be used interactively to be able to exchange insights and stimulate discussion on uncertainties. In the physical sciences, one no longer refers to model validation, but rather to model performance, which is provided by statistical measures such as the root-mean-square differences between model predictions and observed values.

If one wants to describe the orbits of planets, a mechanistic model is a perfect tool. Mechanistic models are even suitable tools when one wants to send men to the Moon. But in situations of many uncertainties and surprises, such tools will not work. In the case of living beings, mechanistic approaches are of limited explanatory power. In the rest of this article modeling human dimensions of global environmental change from the perspective of complex adaptive systems is discussed. From this new perspective, we look at how to design and use models for exploring the future. But first, one of the main seeds of uncertainty and subjective assumptions is discussed: stability characteristics of systems.

MYTHS OF SYSTEMS

Different perceptions of reality can be visualized by different myths of stability, that is the perception of how systems function. According to the equilibrium myth, systems are in equilibrium. External effects can push the system briefly out of equilibrium, but it automatically returns back to the previous equilibrium situation. This myth corresponds very well with the Newtonian-modeling paradigm. Not only the natural system is considered to be in a natural equilibrium, but also the economic system of supply and demand is in equilibrium due to control of the invisible hand. This metaphor from economist Adam Smith, proposed at the end of the 18th century, was a powerful explanation of micro-behavior in order to describe an elegant mechanical description of the macro-level of economic behavior.

The myth of stability can be represented graphically as a ball at the bottom of a valley (Figure 2a). Perturbations only temporarily knock the ball away from the bottom of the valley. An implicit assumption of this myth is that systems have the capacity to damp all kind of disturbances.

An alternative myth is the obverse, namely the myth of instability. Systems are assumed to be very sensitive to disturbances. Every disturbance can lead to a catastrophe. Applied to environmental issues, the myth of instability explains why some people argue that human activities should not be allowed to disturb the natural system. Any

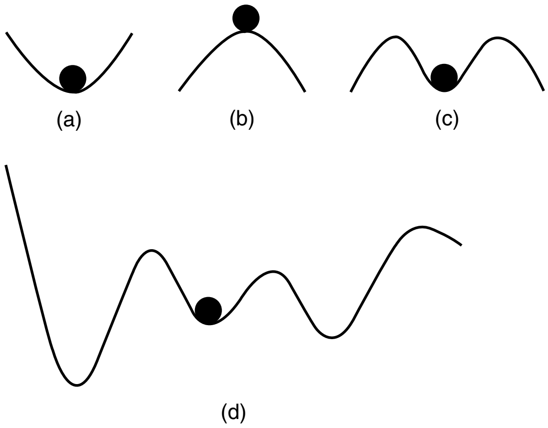

Figure 2 Myths of nature: (a) nature is stable; (b) nature is unstable; (c) nature is stable within limits; (d) nature has different stability domains

degree of pollution or degradation of extraction can lead to a collapse of the system. This myth can be visualized by a ball on a peak (Figure 2b). Any perturbation can lead the ball to roll down the slope.

A third myth is in between the myths of stability and instability, namely a system is assumed to be stable within limits. When the system is managed well, the system can absorb small perturbations. This myth can be visualized as a ball in the valley between two peaks (Figure 2c).

A more advanced framework is to consider multiple stable states. As depicted in Figure 2(d), this myth can be represented as a number of peaks and valleys. The ball is resting in a valley and is able to absorb a certain degree of disturbance. However, an extreme disturbance can push the ball over a peak such that it will rest in another valley, an alternative equilibrium state. Examples of these multiple states are lakes, which can flip from an oligotrophic to a eutrophic state due to inputs of phosphates, and rangelands that flip from a productive cattle-grazing system into a less productive rangeland dominated by woody vegetation, triggered by variability in rainfall.

A myth of systems that is more advanced, and lies in line with the complex adaptive system modeling paradigm, is the myth of resilience.

Myth of Resilience

The myth of resilience does not only consider the balls moving up and down the peaks and valleys, but also considers possible movements of the peaks and valleys themselves. In this evolutionary picture stability domains can shrink, and disturbances that previously could be absorbed no longer can be. This view has important implications for managing systems. From the perspective of the previous myth of systems, systems could be known perfectly. Surprises may lead to changes of management, because the balls moved in another valley, but in principle, management was simply a matter of controlling the system. From the perspective of an evolving landscape, one has to manage a system in the face of fundamental uncertainties over the functioning of the system. One continually observes the system in order to respond adequately. Moreover, small human-induced perturbations are supported in order to learn from the system. This type of management is called *adaptive management* (*see* **Adaptive Environmental Management**, Volume 4).

Holling (1986) has proposed a framework for resilience to explain the transitions in behavior of the system. He distinguishes four basic functions common to all complex systems, and a spiraling evolutionary path through them (Figure 3). This evolutionary cycle can be used to explain transitions in social systems, as well as in ecosystems. The central idea is that the four-phase adaptive cycle emphasizes a loop from conservation to two phases of destruction and reorganization in which innovation and chance assume dominant roles. The reorganization phase occurs when a rare and unexpected intervention or event shapes a new future. In this state, the system is most likely to be transformed by innovation, and agents have the greatest potential to influence the future of the system. When the agents do not react properly to changes in the system, it can flip into a new kind of system.

As mentioned before, the landscape is changing. This has much to do with different speeds of change in the various

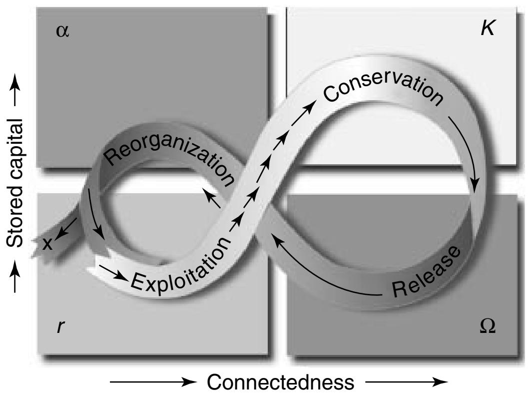

Figure 3 The dynamics of a system as it is dominated by each of four processes: rapid growth (r), conservation (K), release (Ω), and reorganization (α). The arrows indicate the speed of the cycle. The short, closely spaced arrows indicate a slow change, while the long arrows indicate rapid change. The cycle reflects systemic change in the amount of accumulated capital (nutrients, resources) stored by the dominant structuring process in each phase, and the degree of connectedness within the system. The exit from the cycle at the left of the figure indicates the time at which a systemic reorganization into a less or more productive and organized system is most likely to occur. (Adapted from Gunderson and Holling, 2001)

scales of systems. For example, due to phosphorus accumulation in sediments of lakes, recycling of phosphorus from these sediments can lead to surprises. The slow variable, the sediment, can reduce the capability of the lake to absorb an external disturbance. The equilibrium levels of concentration of phosphorus in the water, the fast variable, can therefore change due to changes in the slow variable (Gunderson and Holling, 2001).

According to the myth of resilience, problems could be caused by local human influences that slowly accumulate to trigger sudden abrupt changes that may affect the vitality of societies. There are counteractive forces that give ecological systems the resilience and adaptability to deal with considerable change, and that provide people with the capability to innovate and create. However, nature, people, and economies are suddenly now coevolved on a planetary scale, each affecting the others in such novel ways, and on such a large scale, that large surprises may overwhelm the adaptive and innovative capabilities of people. One challenge of sustainable development is, therefore, how to stimulate coevolution of human activities and environmental change.

Different Perspectives on the Problem of Climate Change

The discussion of myths shows various possible subjective interpretations of reality. The importance of different perspectives for modeling the human dimensions of global environmental change is now illustrated. There are various concepts designed to classify different worldviews. Like the case of modeling paradigms, there is no true classification of worldviews. A contribution, which gives a general description of perspectives on natural and human systems and social relations, has been made by Michael Thompson and his colleagues in their cultural theory (Thompson *et al.*, 1990). This theory has been used to classify different types of institutional designs in relation to global environmental change. The cultural theory has been an inspiration for implementing worldviews in formal models, because it includes perspectives on human as well as natural systems, it claims generality, and its explanation of perspectives' rationalities is deterministic. The cultural theory combines anthropological insights with ecological insights, resulting in different cultural types.

The three main worldviews in the Cultural Theory are the following types:

1. Individualists assume that nature provides an abundance of resources, and remains stable under human interventions. A responsive management style is advocated.
2. Egalitarians assume that nature is highly unstable, and a small human intervention may lead to complete collapse. A preventive management style is preferred.

3. Hierarchists assume that nature is stable in most circumstances but can collapse if it crosses the limits of its capacity. Therefore, control is advocated as a management style.

As discussed earlier, human induced climate change is a topic surrounded with many uncertainties. It is, therefore, an excellent example to illustrate how worldviews can be quantified to simulate alternative futures based on different perceptions of reality. Such an analysis has been made by Janssen and de Vries (1998) who developed a simple integrated ecological economic model for which they implemented three versions based on alternative assumptions on climate sensitivity, technological change, mitigation costs, and damage costs due to climate change. Egalitarians, for example, assume high climate sensitivity, high damage costs, low technological development, and low mitigation costs. For management styles, they assume different strategies for investments and reductions of emissions of carbon dioxide. By contrast, the individualist, for example, assumes a strategy that maximizes economic growth, and emissions are reduced only if a certain threshold of economic damage is exceeded. The hierarchist tries to balance economic growth and climate change by assuming the IPCC estimate of climate sensitivity.

Suppose that all of the agents in a model world share one of the three extreme worldviews. If agents are assumed to have perfect knowledge of their world, their utopia can be simulated. If their worldview is incorrect and they still apply their preferred management style, their dystopia can be simulated. An example is presented in Figure 4. In the egalitarian utopia, emissions of carbon dioxide will be reduced to zero within a few decades, leading to a modest temperature change. However, if the individualistic worldview manages a world that actually operates according to the egalitarian worldview, emissions increase until climate

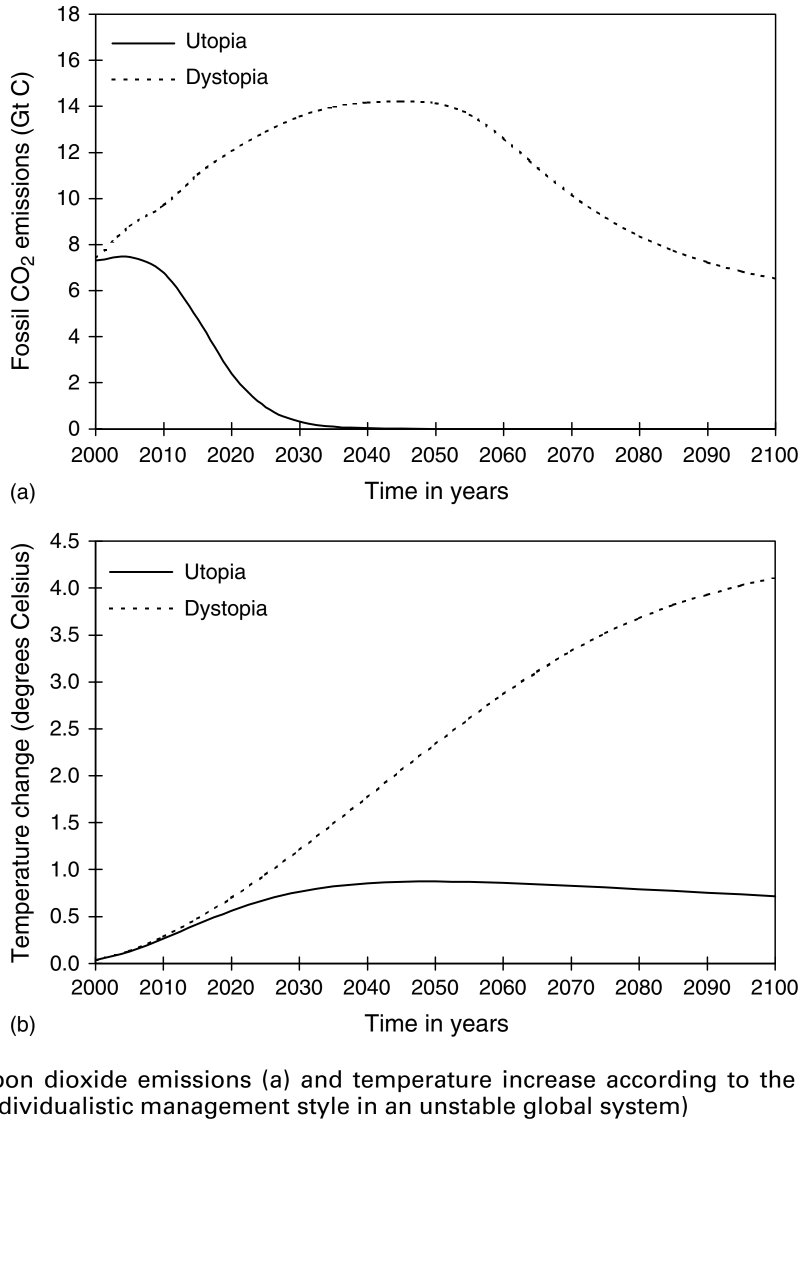

Figure 4 Expected carbon dioxide emissions (a) and temperature increase according to the egalitarian utopia and a possible dystopia (b) (individualistic management style in an unstable global system)

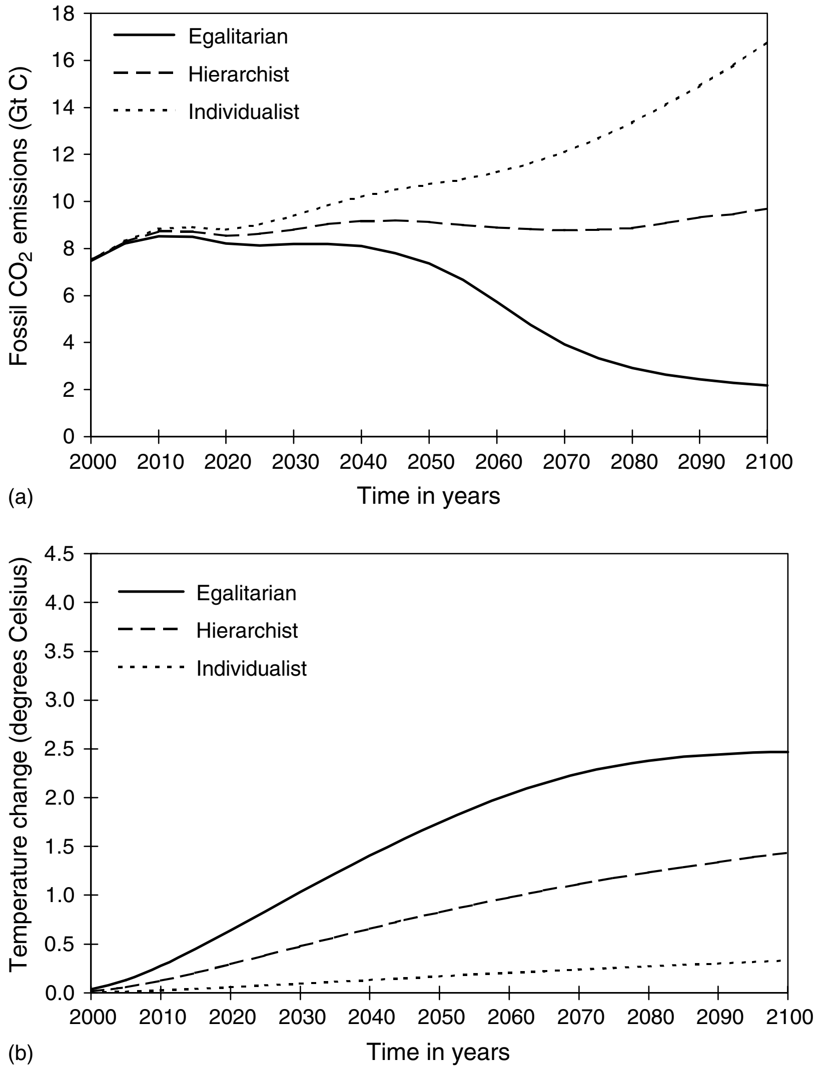

Figure 5 (a) Expected carbon dioxide emissions and (b) temperature increase according to different views on the functioning of the global system, and where the worldviews of agents change in time

change causes such an economic disaster that emissions are reduced by the collapse of the economy.

By introducing a population of agents with heterogeneous worldviews, a complex adaptive system is produced. It is assumed that the better an agent worldview explains the world's observed behavior, the greater is the chance that an agent will not change its worldview. On aggregate, there is a trend towards changing to the worldview that explains the observations in the most likely way. Suppose that reality is one of the three possible worlds, and an agent obtains information over time that causes him to change (or not) his perspective on the climate change problem. Three sets of projections are derived in which agents adapt to climate change (Figure 5). Prior to the year 2040, the observed climate change does not lead to domination of one of the worldviews. After 2040, the climate signal becomes clear enough that one of the worldviews begins to dominate. In the event of the world functioning according to the egalitarian worldview, the emissions growth stabilizes on average in the coming decades and decreases to a level below half the present amount of emissions. However, this reduction cannot avoid a global mean temperature increase of about 2.5 °C in the 21st century.

The explicit inclusion of subjective perceptions of reality has led to a rich variety of possible futures. This will not simplify decision-making, but can improve decision-making since a large set of plausible scenarios is presented. This type of modeling is currently applied in different areas of global and regional environmental change. Each system in which it is not certain that it will remain stable under all kinds of disturbances, can in principle be studied by explicitly assuming different perceptions of reality. It is the expected that this type of modeling will be especially interesting for simulation of institutional dynamics.

MACRO-LEVEL DYNAMICS

Although there are often uncertainties about the relations, global models simulate macro-level dynamics. Here, we focus on the most important macro-level drivers of global environmental change, which are population size, economic development and technological change. In the early 1970s, Paul Ehrlich and John Holden described the environmental impact of society by the well-known IPAT equation: $I = P \times A \times T$. Here environmental impact equals the product of population size, the degree of affluence per person and the environmental impact from the technology used to produce one unit of affluence.

The coming sections discuss three factors that are closely related to the IPAT equation: population growth, material and energy consumption of economies, and technology development. For each factor, empirical information on the macro-scale provides information on possible developments in the long term. However, extrapolating historically derived macro-level relations involves subjective assumptions. Therefore, it is important to explore the consequences of these subjective aggregated relations and to improve understanding of the empirically derived macro-level information.

Demographics and Human Health

Population growth is one of the main causes of global environmental change. The continuing population growth can be explained by changes in demographics and health. The so-called demographic and health transition describes how populations can go through typical demographic and health stages when they change from living in pre-industrial conditions to having a mortality pattern that is found in the post-modern societies (*see* **Demographic transition**, Volume 5).

The shapes of the demographic transition curves are well known, but are in fact a hypothesis based on cross-national and longitudinal studies. In developed countries the demographic transition has reached the final stage. But how will this development of fertility and mortality figures continue in the future? Will the developing countries follow the same transition, and at what rate? Most population projections are based on the assumption that all countries will go through the demographic transition leading to a leveling off of population growth during the 21st century. Observed transitions in demographics are the result of changes in individual behavior, technology and norms, improvement of health care, use of contraceptives, age of marriage, literacy, position of woman, regulation of abortion, etc. It is expected that due to all these variables involved, the demographic transition will not occur everywhere to the same degree and at the same speed. Therefore, subjective assumptions have to be made in order to develop projections for the coming centuries.

Assumptions about the health transition in various regions of the world are even more difficult since various diseases are related to global environmental change (skin cancer due to stratospheric ozone depletion), behavior (lung cancer from smoking), emerging new diseases (acquired immune deficiency syndrome – AIDS) and even some re-emerging old diseases due to the development of new resistances (malaria). It is therefore difficult and subjective to project health conditions of our descendants.

The Material and Energy Consumption of Economies

An economic system can be viewed as a living system, consuming material and energy inputs, processing them into usable forms, and eliminating the wastes. The metabolism of economies has changed significantly during the last two centuries. A world economy has emerged that produces agricultural, and industrial products and services in large volumes, and transports them all over the globe. Agricultural production has increased due to more and more intensive use of land. Productivity has improved due to biological innovations in the form of new crops, new agricultural practices, mechanization, and increasing synthetic inputs. The same holds true for industrial production, which is increased due to the increasing consumption of energy and materials. Currently, the service sector is becoming increasingly important, stimulated by increased personal mobility and more individualistic lifestyles.

These economic developments have led to an increase of material and energy use in absolute figures, but also in *per capita* figures, and have led to all kinds of disturbances of biogeochemical cycles. These disturbances have led to environmental change on various scales.

The debate whether the environment is able to sustain economic development goes back to Thomas Malthus at the end of the 18th century, who argued that food production could not be increased quickly enough to keep pace with the growing population. But due to a faster increase of agricultural productivity than expected, a decrease in birth rates, and the growing import of food, Malthus' homeland (Great Britain) did not collapse. Since the early 1970s, stimulated by the *Limits to Growth* report of the Club of Rome, the debate on economic growth and the environment has emerged again.

In the last 30 years, there have been attempts to improve the physical reality of economic models by including mass balance conditions, and laws from thermodynamics. However, there is still no clear theory on the relation between economic development and the environment. In the 1990s a lot of empirically based studies were published on the relation of environmental pressure of an economic system and the average income. This so-called Environmental Kuznets curve (see, for example, de Bruyn, 2000) (Figure 6) consists of three phases:

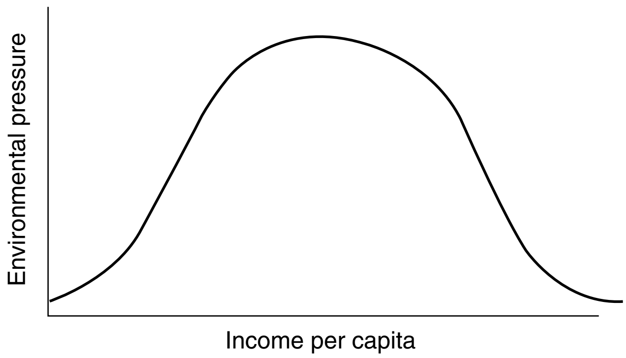

Figure 6 Environmental Kuznets curve

1. initially income growth parallels progressively increasing environmental pressure;
2. next, further income growth leads to increasing environmental pressure until it reaches a maximum;
3. further income growth leads to a reduction of environmental pressure.

An explanation for this pattern is that at higher income levels, individuals will attach more value to environmental quality; this means more income spent on less damaging consumption, as well as more democratic support for stringent environmental policies. An important implication of the environmental Kuznets curve is that growth by itself would be able to solve environmental problems. However, the empirical support for this hypothesis is weak and mainly based on cross-sectional analysis. It is not clear whether the curve differ for different types of environmental pressures, what is the influence of policy measures and technological change, and whether observed trends in the past will continue in the future. Some studies suggest that delinking of environmental pressure and economic output has only been a temporary phenomenon caused by efficiency and technology improvements after the oil crises of the 1970s (de Bruyn, 2000). The cheap energy prices of the 1990s led to a relinking of environmental pressure and economic output. Despite the many uncertainties, relationships between physical and financial dimensions of economic systems like the environmental Kuznets curve are used to explore future material and energy consumption.

Technological Change

Technology development is the source and remedy of environmental change. This is called the paradox of technology and the environment. It is the source, because it creates the ability of societies to mobilize more materials and energy, and because it creates new materials and substances with direct environmental impacts. On the other hand, technology can also be the remedy because it increases productivity and efficiency of economic activities and invents specific technologies to prevent pollution.

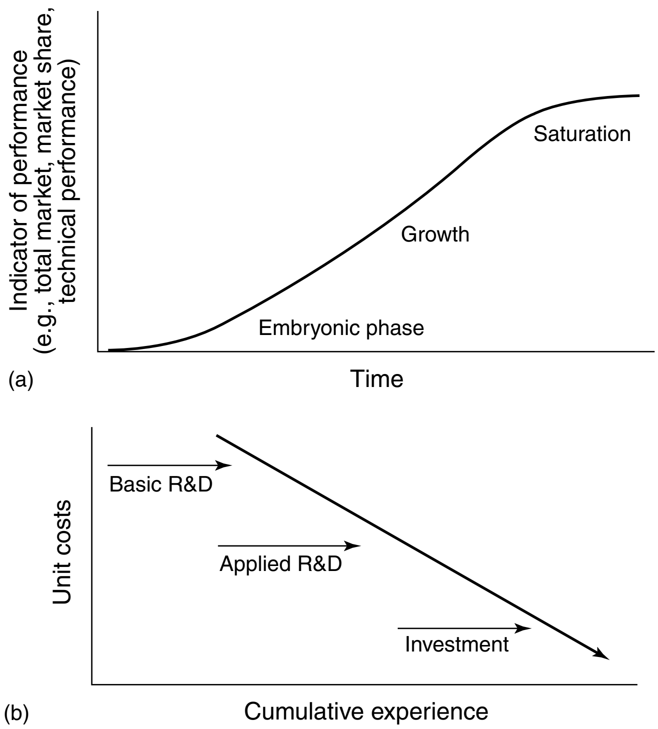

Figure 7 (a) a stylized technology life cycle; (b) a stylized learning curve, where axes scales are logarithmic. In the beginning costs decrease due to basic R&D. When the potential of the technology is demonstrated, applied R&D investments reduce the costs further until a level is reached for which costs are competitive. (Adapted from Grübler, 1998)

It is therefore important to understand the dynamics of technological change. Arnulf Grübler (1998), in his book on technology and global change, discusses general mechanisms on the diffusion of technology. The question is how a new technology is adopted at a large social and spatial scale. This can be visualized by the stylized technology life cycle (Figure 7a). In the beginning, a new technology is imperfect, and various possible designs are explored. The market effect is small, but the increase that occurs during the growth phase is characterized by increasing standardization and falling costs. Finally, the growth rate slows down as the market becomes saturated. In this phase the market is in the hands of a few suppliers.

Technology life cycle is related to the developments of costs. There is a lot of empirical evidence that the decrease of a technology investment cost is related to the accumulated investments in the particular technology. This learning-by-doing can be formulated by the technology learning curve (Figure 7b). The costs (on a logarithmic scale) decrease linearly with an increase in cumulative experience (on a logarithmic scale). The main uncertainty of technology in the early phase of development is the slope at which the costs decrease.

In mainstream economic models, technology is often included as an exogenous variable. Such an assumption leads to wait-and-see policies because investments are delayed until clean technology has become available at suitable cost levels. Such a policy differs from insights derived from the learning curve, which suggest stimulation of investments in clean technology allowing costs to decrease.

Insights into technology dynamics show stylized facts derived from empirical studies. This provides tools for modeling technology development. The main question is how does an individual technology penetrate the market, and how can governmental policy stimulate the diffusion of green technology? Many decisions of individuals influence this evolution. Therefore, we need to have more insights into models of human behavior.

UNDERSTANDING THE EMERGENCE OF STYLIZED FACTS

The observed stylized facts, the observed macro relations, are the result of decisions of many agents. They are emergent properties of a complex adaptive system. To improve our understanding of these observed stylized facts, we should develop tools to understand them. One way is to use models that are able to simulate these emergent properties from the bottom up. Like the cartoon (Figure 8), understanding of macro level phenomena can only be derived by studying the behavior of micro level agents. In the case of a school of fish, multi-agent studies have shown that flocking behaviour can be simulated by using three simple rules for each agent:

- separation: steer to avoid crowding local flockmates;
- alignment: steer towards the average heading of local flockmates;
- cohesion: steer to move toward the average position of local flockmates.

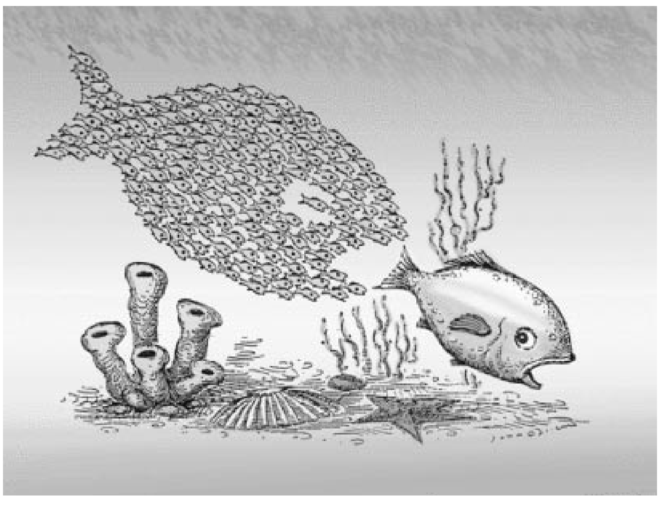

Figure 8 Macro level phenomena emerge from behavior of agents on the micro level

Behavior of human agents is much more difficult to capture by simple rules. Two types of human behavior can be distinguished: individual behavior, and behavior of groups and institutions.

Individual Behavior

Since theory development in social science is rather fragmented, various models of human behavior exist. In fact, different disciplines study only particular aspects of human behavior. One central element, or better, one stylized problem, is found in most models of individual behavior. Humans are assumed to maximize their well being given budget constraints. These budget constraints mainly relate to income and time. Within economics and psychology, different variations exist on this stylized problem. In the formal approach of conventional economic theory, this means that the rational actor, the *Homo economicus*, maximizes its own well being. This *Homo economicus* is assumed to have perfect knowledge of the system in order to find the global optimum. In the case of uncertainties, the probability distributions are perfectly known. These assumptions make it possible to formalize human behavior in an unequivocal way. A drawback is the existence of much empirical evidence that real humans do not behave in this way. For example, experiments show that humans discount the near future at a higher rate than the distant future, experience well-being with relative changes instead of absolute levels, and are about twice as averse to taking losses as to enjoying an equal level of gains (e.g., Thaler, 1992).

Some economists, like Nobel Laureate Herbert Simon, argue that humans are rationality bounded. First, no person can ever assemble all the information required for an optimal decision. Second, even if one could, decisions are usually so complex that no simple algorithm exists for evaluating all possible options. Third, a person's own decisions depend on the decisions of other persons. Simon argues therefore that humans satisfice instead of maximize their well being. A consequence of relaxing the assumption of maximizing behavior is the large set of possible rules that describe behavior. The formalization is not unequivocal anymore. Thanks to the development of new simulation techniques such as cellular automata, genetic algorithms and neural networks, and the widespread availability of personal computers, social scientists are exploring new ways of modeling human behavior (e.g., Gilbert and Troitzsch, 1999).

Psychologists and other social scientists include different indicators than are usually used in economics. Psychologists focus on satisfaction of various types of needs such as understanding, freedom, identity and leisure. Furthermore, all humans are different. They differ in their abilities, mental models, preferences and opportunities. In contrast with *Homo Economicus*, decisions depend on social interactions, as well as on individual considerations. In fact, humans are assumed to perform different cognitive decision processes in different situations.

The mental models of humans are important elements in cognitive processing. Differences in perceptions of reality can result in different behavioral patterns. Although humans can learn, they will never have the perfect knowledge that is needed to maximize well being as performed by *Homo Economicus*. This picture of human behavior is in line with the complex adaptive system-modeling paradigm. Since humans cannot perfectly control their own situation, they design institutions to regulate human interactions, as well as interactions between society and the environment.

Institutions and Collective Actions

Institutions contain formal constraints (rules, laws, constitutions), informal constraints (norms of behavior), and their enforcement characteristics. They shape human interactions and the way societies evolve through time, and can also be important to regulate human activities in relation to ecological conditions. A stylized problem that is generally used to study institutions is the so-called *commons dilemma*, widely discussed as a result of the well-known analysis of Garrett Hardin on the *Tragedy of the Commons* (*see* **Commons, Tragedy of the**, Volume 5). According to this analysis, the commons tend to be overharvested since each agent harvests to the point where private costs equal the benefits, whereas harvesting imposes additional social costs on the rest of the community. However, historical analyses of common resource properties have found many examples where the tragedy did not happen (Ostrom *et al.*, 1999). Communities often had ways of self-organizing to prevent overexploitation of the commons, also known as closed commons. Success of self-organization depends heavily on the characteristics of property-right systems. The tragedy of the commons is an example of open access, where everybody can harvest without individual punishment. However, other types of property regimes to regulate common resources are related to group, individual and governmental property.

The success of self-organization of effective institutions to control common resources depends on property regimes, as well as evolution of norms and design of rules. Again, this is an excellent example of complex adaptive systems.

DIFFERENT WAYS OF USING MODELS

It should be clear by now that models are not of use to accurately predict future developments of human dimensions of global environmental change. Although models are often used for this purpose, there are more suitable purposes for which they are of importance. In fact, they can be used to overcome the problems raised during the analysis of the current generation of integrated assessment models. Instead of focusing on a single model used for prediction, a combination of different types of models should be used to explore hypotheses and uncertainties. Models can be used in different ways. Here, three different goals of use are distinguished: to understand observed stylized facts, to improve decision-making of complex problems due to interactive use of models, and to explore possible futures by scenario developments.

Understanding Stylized Facts

In the descriptions of the various sectors a number of stylized facts were identified, such as the demographic and health transition, diffusion of technology, and environmental Kuznets curves. These macro-level observations are the result of behavior of agents at smaller scales. To understand stylized facts, and to explore possible changes in macro-level relations, we need to study the behavior of the underlying components. Can we explain the diffusion of technology by using simple rules for agents? Under which assumptions can an environmental Kuznets curve be simulated by micro-level decisions of economic agents?

This type of question relates to current work in evolutionary economics. Various studies analyze what are the important characteristics of firms and technology development to explain structures emerging in specific markets. Examples are the size distribution of firms, and the large number of firms during the beginning of a new market. Such analyses are also frequently performed by various other disciplines, and are assumed to be valuable to understand the underlying dynamics of the observed stylized facts.

Interactive Use of Models

Models are not prediction machines, and should not be used in this way. Moreover, for policy analysis, models should be made available in such a way that they can be used in an interactive fashion. The recent developments in graphical user interfaces, PC availability and Internet, should make it possible to use simple transparent models by a large community of stakeholders. Models can be used in this way as learning tools. Using models in this way is exactly what we can learn from the work of Dörner (1996).

Dietrich Dörner and his colleagues study decision-making in complex situations. Their research design is to develop micro-worlds, which are computer simulation models of a management problem, and to ask real persons to manage the system. These management problems vary from a simple climate-control system to regulation of a virtual society. Because the participants in the game have an incomplete picture of reality, their attempts to manage the system can lead to catastrophes. Dörner concludes that managing complex situations requires experience, and this experience can be built up by playing management games, like training pilots in flight-simulators.

Scenario Development and Alternative World Views

Traditionally, scenario analysis starts with an initial forecast which is called the base case or reference scenario. Then alternative assumptions are made of initial conditions, equations and parameter values. The resulting projections are called *scenarios*. Differences between the scenarios and the references are used to evaluate uncertainties and possibilities of policy to influence the future. However, due to the implicit assumptions within every model, one reference scenario will not be enough to assess policy options. In fact, a set of reference cases should be used, which capture the main variety in alternative assumptions (Rotmans and de Vries, 1997).

Scenario analysis should be seen as "computer-aided" storytelling, where different stories can serve as a starting point for analysis. Analyzing policy options for different types of futures, can give insights into the robustness of these policies. Explicitly using different starting points can reduce the illusion that model-based analyses are objective predictions. In such a way, models can serve as a medium for discussion instead of an electronic oracle.

CHALLENGES FOR THE FUTURE

Important weaknesses of current modeling activities, related to human dimensions of global environmental change, are the inherent subjective assumptions of parameter values and relationships, and the fact that macro-relations are used of phenomena which emerge from local interactions between agents.

The challenge in the coming decades will be to use new developments in modeling tools and the use of models to overcome current problems. A promising start can be made when models are used in a more explorative way. Current models are often used as truth-machines. But the predictions, the glimpses of the future derived from electronic oracles, should not be our main interest. Since the future is inherently unpredictable, models should be used to enrich our insights into the behavior of complex reality. Improvements of our mental models can help us to improve our decision-making.

The concept of complex adaptive systems can be a promising starting point to think about new ways to develop and use models concerning human dimensions. Systems evolve, and therefore models assessing the future should focus on evolution and change. This requires the inclusion of disciplines nowadays not highly involved in modeling, such as psychology, institutional science, history and anthropology. Modeling human dimensions of global environmental change is a way of managing uncertainty and complexity. The tools discussed in this article can help us to experience and learn this art.

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