# Qualitative Reasoning and Global Change Research: Experiences from Modeling Human-Environment Systems for Policy Advice*

**Gerhard Petschel-Held**
Potsdam Institute for Climate Impact Research
P.O. Box 601203, 14412 Potsdam, Germany petschel@pik-potsdam.de

## Abstract

In recent years qualitative modeling has found its way into the transdisciplinary field of sustainability science. Here, "transdisciplinarity" refers to the close interaction between science and policy making, e.g. questions are often raised by decision makers and results need to be simple and comprehensible. "Sustainability science" refers to a highly complex issue, integrating ecological, economic, and social dimensions with the objective of finding ways towards a "better" future. The paper gives an overview on the requirements and condition for modelling in this field and illustrates possible contributions of qualitative reasoning along a set of examples. At the end, the expereinces made are put forward into a a list of needs and new approaches for further improvements of the applicability of QR in the field.

## 1 Introduction

Environmental science is a long existing field of research, focussing primarily on the natural effects of human activities like energy production, traffic, or construction. Within this field problems like pollution have been investigated, e.g., with regard to the distribution by atmospheric transport or its ecological effects. As it has become obvious that the scale of these impacts have now reached a global scale, e.g. the evident human-driven change of the global climate, the reduction of ozone in the higher levels of the atmosphere, especially over Antarctica and more recently over the Arctis also, or the reduction of biological diversity. Furthermore, evidence increases that these changes have a significant impact on human well-being, e.g. material income, human health and security. This "closing of the loop" has created a major challenge for science which is called to provide a basic understanding of the natural and the social processes governing these global changes [Steffen *et al.*, 2004].

This challenge to science is confronted with some major obstacles for the traditional way of scientific analysis. Maybe most pronounced is the lack of experimental setups to study these processes on the global scale. On the other hand, we are facing a vast variety of geographical contexts in terms of cultural, social and also natural determinants for human-environment systems. Furthermore, some, if not most, of the knowledge available is qualitative in nature and any kind of quantification is either not available yet or might also be not possible in principle, e.g. culture, politics, etc. These examples already illustrate that there appears to be a vast field of potential application for qualitative reasoning. In recent years, some first steps have been made to apply QR into this challenging field of global change research. The present paper seeks to give an overview on some of these approaches with an emphasis on qualitative differential equations [Kuipers, 1994].

The paper starts by formulating some requirements for modeling and "logic argumentation" when applied within the field of global change research (Sec. 2. In Section 3 examples will be given for applications of qualitative reasoning which seek to meet those problems and requirements. Based on the experiences from these examples, the final section will list some essential needs for progress in the field of qualitative reasoning when it comes to its applicability to global change research.

## 2 Requirements for Modeling

Within global change research, models are used for a variety of questions. Most prominent are models of the global climate which come in different levels of complexity. Here models are mostly used to study the implications of atmospheric composition, e.g. the concentration of radiative active trace gase like carbon dioxide (greenhouse gases), for the temprature and precipiation distribution across the world. Models are also used to study and understand the history of the Earth's climate. Similarly, models are used to investigate the implications of climate for vegetation and agriculture. These models might be seen as both, creators of scientific hypotheses as well as experimental setups for testing.

When it comes to the human realm, the philosphy of model usage shifts. As there is a wider range of competing scientific theories, models are often seen as a means for justification. Because many of these models are equally good and valid with regard to the reconstruction of real world data, models are used to justify certain actions. An example is the ongoing

*The work described here includes help and input from Klaus Eisenack, Jürgen Kropp, Matthias Lüdeke, Diana Meyer-Veden, Diana Sietz, and Oliver Walkenhorst

debate about the actual costs for reducing the anthropogenic emissions of greenhouse gases. The latter is necessary to avoid a dangerous climate change, which is a target the international community has agreed upon in 1992 within the UN Framework Convention on Climate Change.

In general, the usefulness of models in global change research comes from their very strength of "giving logical implications of explicit assumptions" (Steve Schneider, pers. communication). Nevertheless, further difficulties arise from the fact that this field of research is not (solely) pure science, but also has a strong science-policy interface. When evaluations of political actions and strategies are sought for, the needs of decision makers need to be taken into account: What do they want to know? What variables are within their field of experience and decision making? What can and what they want to influence? This amalgamum of issues raises some special requirements for modeling which not only seem to be particularly suited for qualitative reasoning methods, but which are also of wider relevance.

1. *Qualitative Knowledge*: For many of the aspects to be considered only qualitative knowledge is available. Take, for example, the realm of human decision making. Though a wide range of theories are available, ranging from optimal choice via bounded rationality to "muddling through", the quantification of these theories is often only be possible in an ex-post analysis of decisions taken in the past. Yet we cannot be sure that the functions and numbers unconsciously used in earlier decisions, still hold in the future. Though we can also be not sure whether the qualitative aspects, i.e. I prefer X over Y, also holds in the future, the assumption that they actually still hold is more robust.

   Qualitative knowledge also prevails when the quantification of "issues" itself are problematic or highly debated. Take, for example, the issue of poverty. Though it is generally agreed that poverty does play a major role in Global Change, its indication by measurable numbers is argued since the very first moment the issue entered the international debate.

2. *Geographical Variability*: The focus of the analyses in global change research are human-environment systems. When studying these systems on small scales, e.g. villages or provinces, researchers often claim that the system varies heavily from place to place. Yet, the question is, how different and different with respect to what. Often the systems share the same variables and maybe also the existence of interactions between variables. They might differ by the functions relating the variables, but not by the qualitative properties of these functions, e.g. monotonies. In this sense a qualitative modeling approach can bridge these differences by looking at the more general qualitative properties only [Petschel-Held and L¨udeke, 2001].

3. *Communicability*: When models are directly used in a science-policy dialogue, they need to be simple and comprehensible [van Dalen *et al.*, 1998]. Note that this not necessarily holds, if model outputs are used to assess *before* communicating with decision makers or the wider public, i.e. when scientific results are presented as clear facts and not if policy measures are to be investigated interactively. Comprehensibility not only refers to the way, how the results are presented, but also to the content of the model. Experience shows, that decision makers want to understand what is happening inside of the model, what its assumptions are, and what it is based on. Yet, they also have a preference for numbers, which probably rests on the prevailing assumption that science is only exact if it produces such numbers.

4. *Conceptual Knowledge*: Besides "scientific modeling" based on theories and data, the mental models of decision makers are of particular interest in the field of global change research. How do decision makers envisage the world? How do they perceive causes and mechanisms of change? In order to present decision makers with the implications of their mental maps, it can be useful to develop a formal representation of these maps. Within a dialogue process of so-called group modelling, these maps are put into a formal framework and the outcomes of these formal representations are discussed. These can lead to new questions, modifications of the mental maps, and a more thorough understanding.

## 3 Applications

Within this section, some qualitative modelling approaches are discussed which have been developed by modelers from the global change research community. It is particularly discussed, how these approaches can meet some of the requirements discussed above.

### 3.1 Qualitative Knowledge: Agriculture in North-East Brazil

Agriculture in North-East Brazil is dominated by smallholder farmings on rather nproductive grounds. This induces an increased vulnerability to droughts which occur frequenty about once or twice per decade. Smallholders often do not have the means to cope with droughts are caught in poverty. In addition, the "regular" dynamics is determined by an increasing loss of productivity due to soil degradation, e.g. by erosion.

In order to understand this dynamics, a model has been developed which makes use of qualitative differential equations [Sietz *et al.*, 2004]. The model used the C-Version of the QSIM algorithm, developed at the Potsdam Institute for Climate Impact Research [Eisenack and Petschel-Held, 2002]. The model has been based on the general knowledge and literature from the region. Droughts are not endogenous to the model, but their effect can be studied using the resulting graph of qualitative dynamics. Unfortunately, the data basis is too weak for a throrough validation of the model, but according to expert judgment the overall structure of the dynamics is reasonable and thus can be used to study implications of droughts and governmental programs to improve the livelihoods of the local smallholders.

### 3.2 Case Study Integration: Smallholder Agriculture

Smallholder agriculture is not only a problem in Northeast Brazil, but constitutes a major element of sustainability problems throughout the developing world. In order to get an overall impression on the processes governing the dynamics of smallholder agriculture a set of 22 case studies throughout the tropics has been evaluated. The basic idea is that the local situations in these regions share the same qualitative properties, i.e. the functions describing the processes within a model share the same monotonicity properties. Furthermore the case studies were evaluated with respect to the qualitative dynamics in the region. If the qualitative trajectory of a region is found in the model output, the model can be considered as being not falsified for the region. In this sense, qualitative modelling can be used as an integrative tool for the comparison of case studies [Petschel-Held and L¨udeke, 2001].

The general QDE model included a total of 30 variables of which five variables were considered as being independent, thus characterizing the local context. Focus of the analysis was in which of these contexts smallholders can cope with impoverishment, environmental degradation or both. For this a "locking analysis" was performed, in which the result graph is analysed with respect to subsets where the qualitative values of some variables remain constant and do not have successors where these variables do change [Eisenack, 2003].

It turned out that three of the context variables are decisive for the existence of locked sets with respect to environmental degradation and impoverishment, i.e. the aquisition of new knowledge by smallholders, population growth and the natural productivity of the region. This gives further insights into the causes for the so-called environment degradation spiral [Petschel-Held *et al.*, 1999; Kates and Haarman, 1992].

### 3.3 Communicating with Decision Makers: Modelling Urban Sprawl

Urban sprawl describes a process of urban change characterized by an increase in the build-up area together with a decrease in density. Within an international project funded by the European Commission, qualitative modelling was intended as an integrative tool to describe the processes of urban sprawl in seven metropolitan regions in Europe assessed by individual case studies. It was the goal of the project to provide insights and tools for better managing urban sprawl which the European Union sees as a necessity for improving the quality of life. Therefore the project also included a close interaction with urban planners and governments, e.g. with respect to the usage and application of the model. This took place with two so-called stakeholder workshops and one training workshop. Two of these workshops focused the communication of the model and its results as well as its implication for urban sprawl management.

In general, planners and urban governments found the model a useful tool for improving their knowledge basis on urban sprawl. Interestingly enough the main benefit did not come from the model results, but from its underlying assumptions and hypothesis. The usability of the model therefore came from the validation of these assumptions by its own validation on basis of the findings of the individual case studies.

### 3.4 Conceptual Knowledge: Sustainable Development in The Netherlands

Within the SCENE project, Grosskurth and Rotmans developed a participatory modeling approach using the qualitative systems analysis tool from the Santa Fe Institute [Grosskurth and Rotmans, 2004]. Within this exercise stakeholders in the issue of water basin management in the Netherlands were interviewed about their perception of relative issues and their interactions. This information was collected within the qualitative systems approach by counting the numbers at which variables and interactions were mentioned by the stakeholders. As a result, the most important variables and interactions are identified which then was used as a basis for quantitative modelling based on the most relevant variables and interactions.

## 4 Further Needs

The experiences made with qualitative models within the field of global change research give clear hints on needs for improving qualitative reasoning approaches. These improvements are necessary to enhance the usability of these approaches which are perceived as being potentially strong due to their reliance on qualitative and incomplete knowledge.

Of particular importance the following issues can be mentioned:

- *Reducing the Output Space*. Decision makers expect scientists to reduce the uncertainty about the future. Often, the outputs of qualitative models are very comprehensive, not allowing statements beyond a "either this or that can happen, but we don't know which." It is therefore important to improve qualitative modeling approaches to reduce the number of possible solutions. Of course, this often requires the use of further information in the model building phase. Some recent progress has been made at the Potsdam Institute by using information on the order of partial derivatives within multiple variance constraints.
- *Communicating the Results*. The focus on the presentation of the results of qualitative models so far is, of course, on its exactness. Unfortunately, these kinds of graphs and diagrams are not very appealing for non-experts. This definitely limits the application of qualitative models. Therefore methods have to be developed to translate these graphs into more appealing presentations without loosing exactness. The only way this appears to be possible is by reducing the information given from the completeness it seeks for the time being to elements which are seen as most important and relevant for decision makers.
- *Bridging the gap to quantitative models*. Quantitative modeling is widespread in global change research. Models for climate, vegetation or hydrology, but also for the economy are regularly used for analysis and policy advice. In many instances these models are coupled, either consequtively or in a back and forth manner. Many of these models find their limits when it comes to qualitative knowledge, e.g. within the social science realm. It

would therefore be useful to develop methodolgoies to couple qualitative with quantitative models.

In summary, it can be stated, that the application of qualitative reasoning approaches within global change research has made some progress, but without further conceptual improvements along the lines indicated, this progress will fade.

## References


[Eisenack and Petschel-Held, 2002] Klaus Eisenack and Gerhard Petschel-Held. Graph theoretical analysis of qualitative models in sustainability science. In *Proceedings of the 16th International Workshop on Qualitative Reasoning*. 2002.

[Eisenack, 2003] Klaus Eisenack. Qualitative viability analysis of a bio-socio-economic system. In *Proceedings of the 17th International Workshop on Qualitative Reasoning*. 2003.

[Grosskurth and Rotmans, 2004] Jasper Grosskurth and Jan Rotmans. New knowledge for sustainable governance: The scene model. In Frank Biermann, Sabine Campe, and Klaus Jacob, editors, *Proceedings of the 2002 Berlin Conference on the Human Dimensions of Global Environmental Change "Knowledge for the Sustainability Transition. The Challenge for Social Science"*, pages 32–42, Berlin, Potsdam, Oldenburg, 2004. Global Governance Project.

[Kates and Haarman, 1992] Robert W. Kates and V. Haarman. Where the poor live: Are the assumptions correct? *Environment*, 34:4–11,25–28, 1992.

[Kuipers, 1994] Benjamin Kuipers. *Qualitative Reasoning: Modeling and Simulation with incomplete knowledge*. MIT Press, Cambridge, MA, 1994.

[Petschel-Held and L¨udeke, 2001] Gerhard Petschel-Held and Matthias K. B. L¨udeke. Integrating case studies on global change by means of qualitative differential equations. *Integrated Assessment*, 2(3):123–138, 2001.

[Petschel-Held *et al.*, 1999] Gerhard Petschel-Held, Arthur Block, Martin Cassel-Gintz, Jrgen Kropp, Matthias K. B. L¨udeke, Oliver Moldenhauer, Matthias Pl¨ochl, and Hans-Joachim Schellnhuber. Syndromes of global change - a qualitative modelling approach to assist global environmental management. *Environmental Modeling and Assessment*, 4(4):295–314, 1999.

[Sietz *et al.*, 2004] Diana Sietz, Bianca Untied, Oliver Walkenhorst, Matthias K. B. L¨udeke, G¨unter Mertins, Gerhard Petschel-Held, and Hans-Joachim Schellnhuber. New modelling methods for heterogenous human-environment dynamics. smallholder agriculture in semi-arid northeast brazil. *Regional Environmental Change*, submitted, 2004.

[Steffen *et al.*, 2004] Will Steffen, A. Sanderson, Jill J¨ager, P.D. Tyson, Berrien Moore III, Pam A. Matson, K. Richardson, F. Oldfield, Hans-Joachim Schellnhuber, Bill L. Turner II, and Robert J. Wasson. *Global Change and the Earth System - A Planet under Pressure*. Global Change - The IGBP Series. Springer-Verlag, Berlin/Heidelberg/New York, 2004.

[van Dalen *et al.*, 1998] Els van Dalen, Wil Thissen, and Marcel Berk. The delft process: experiences with a dialogue between policy makers and global modellers. In Joseph Alcamo, Rik Leemans, and Eric Kreileman, editors, *Global Change Scenarios of the 21st Century. Results from the IMAGE2.1 Model*, pages 267–286. Pergamon, Oxford, 1998.