Qualitative Representations of Indicators of Environmental Sustainability of the Millennium Development Goals

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Abstract

The Millennium Development Goals (MDG) is a set of 8 goals and 18 targets aiming to alleviate poverty and hunger, improve education, reduce gender inequality, reduce mother and child mortality, assure environmental sustainability and promote global cooperation for the development by 2015. The goal related to the environmental sustainability (MDG7) is the more complex and difficult to address. There is no clear understanding on what sustainable development is and how ecological problems are related to it. For most of the indicators either there is no data or the data available is not of good quality. This paper reports the use of Qualitative Reasoning to build (pencil and paper) conceptual models that became the basis for a written national report on MDG7 in Brazil. The paper describes also the implementation of one of these models in a qualitative simulator, establishing causal relations between deforestation and loss of soil and biodiversity, degradation of water resources and poverty. Simulations with this model allow the user to explore different aspects of the problem and to follow the behaviour of three indicators officially designed for monitoring the MDG7. This approach was welcomed as innovative and raised expectations about the use of qualitative models for improving public understanding of current ideas about environmental sustainability.

1 Introduction

Time has come for a global effort to reduce poverty and to increase human development in developing countries. This is the message of the Millennium Declaration, signed by some 190 heads of State in 2000 at the United Nations (UN). As a consequence, discussions on poverty, hunger, education, gender, health, environment and cooperation held over the past 20 years in conferences, protocols and conventions that happen under the UN umbrella were summarized in a set of 8 goals and 18 targets to be achieved mostly until 2015. These goals are known as the Millennium Development Goals (MDG), and 48 indicators were selected to monitor the progress of the countries towards them.

The MDG are different: for the first time, the UN launched a campaign throughout the world to disseminate ideas about human development and sustainable development for the general public, in favour of the MDG. National governments are expected to produce periodically national reports and publicize the situation of the Millennium Goals. As posed by the UNDG [2001], these national reports have to be clear, objective, and understandable for the "average citizen". The idea was to create a feeling that 'we can do' something about the goals. By strengthening public participation and increasing accountability, it is believed that governments and society will do their best in order to meet the MDG.

Among the MDG, the seventh (ensure environmental sustainability) is the most difficult to be understood and to be achieved on time. In fact, all the nearly 40 national reports published so far mentioned difficulties with the MDG7 [Lee and Ganimé, 2003]. Reasons for that include conceptual problems in defining sustainability, and problems to select (or create) indicators to monitor the MDG7, other than those defined by the UN. Basically, for experts there are hypotheses and commonsense knowledge about environmental sustainability and, for the public, less than that. In developing countries, despite the efforts of UN agencies, data about indicators of environmental sustainability do not exist or are incomplete, based on poor quality statistics, often expressed in qualitative terms. Finally, there are problems in communication with the public: environmental issues are poorly understood and indicators in general are presented as lists of data, unrelated to other indicators and without references to causal relations.

Qualitative Reasoning [Weld and de Kleer, 1990] may be useful to address sustainable development related problems, as pointed out by some authors. For example, Struss [1998] argues in favour of a model-based approach to environmental decision making; Eisenack and Petschel-Held [2002] apply special QR techniques to interpret regional land-use changes due to small-holders agriculture in developing countries, and Salles [1997] investigated different qualitative approaches to ecological modelling.

The added value of qualitative models as tools to support the understanding of physical and ecological systems was already recognized. The objective of the work described here is to increase understanding of the general public on environmental issues by building conceptual models based on a QR approach, involving the indicators selected for the MDG7. These models were the basis for a written independent national report produced by the Academic Laboratory for monitoring the MDG at University of Brasília and was delivered to the public in March 2005.

As a ‘proof of concept’, the present work describes the implementation of one of these conceptual models included in the Brazilian report. This qualitative reasoning model integrates in a unique socio-environmental system three of the indicators selected for monitoring the MDG7: land covered by natural vegetation (target 9, indicator 25), land designed to protect biodiversity (target 9, indicator 26) and population without access to safe water supply (target 10, indicator 30).

This paper is organized as follows: the next section presents an overview of the main frameworks designed to organize environmental indicators. Section 3 discusses the use of conceptual qualitative models in the Brazilian national report on MDG7. The implemented model and the results obtained in simulations are presented in section 4. Finally, discussion and final remarks are presented in section 5.

2 Environmental sustainability: how do know if we are getting there?

The most common definition of sustainable development was presented in 1987, on the Brundtland Report *Our Common Future*: it is “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” This definition, however, misses a number of important points in biophysical, economic, social and cultural aspects. For example, the notion that sustainability is a condition of dynamic equilibrium between availability and use of resources and between production of waste and pollutants and the natural capacity for absorbing and metabolizing them. In fact, sustainability is a concept under construction, and a unique definition for it does not exist. Different paradigms to classify the relationship between environmental management and development may be identified [Colby, 1991]. Current ideas on sustainable development include integration between economy and ecology (economic decisions to have regard to their environmental consequences); intergenerational obligation (current decisions and practices to take account of their effect on future generations); social justice (everybody have an equal right to an environment in which they can flourish); environmental protection (conservation of resources and protection of the non-human world); quality of life (a wider definition of human well-being beyond narrowly defined economic prosperity); participation (institutions to be restructured to allow all voices to be heard in decision making) [Connelly and Smith, 1999].

Although previous efforts to review and organize international initiatives in the creation and use of environmental indicators at the UN (Shah, 2000), the Conference on Environment and Development in Rio de Janeiro, 1992 (Rio’92) became a landmark in the history of environmental and sustainability indicators. This issue is so relevant that the Agenda 21 has a chapter (40) to point out the requirements of adequate indicators to monitor sustainable development.

According to Bakkes *et al.* [1994], an indicator is a way of summarizing large quantities of data to a simple form, yet retaining their essential meaning. Thus, indicators must have a wider significance than their face value. Also, indicators are principally normative, that is, they must be comparable with an aim or reference value. The purpose of environmental indicators is to steer action. This way, indicators differ from other pieces of numerical information in that they are elements of a specific steering process, or control process. Environmental indicators can be used to assess environmental conditions and trends on a certain scale, to compare different countries or regions, to forecast and project trends, to provide early warning and to assess the conditions of a system in relation to goals and targets [Bakkes *et al*., 1994].

A number of indicators were developed and included in international initiatives. The interested reader may find more information about the history of environmental indicators in [Bartelmus, 1997], [Shah, 2000b], [ECE, 2001], [CSD, 1996] and [UNSD, 2004], among others. Of our interest here is the Pressure, State and Response (PSR) framework, one of the most influential approaches for classifying environmental indicators[1].

The PSR framework was created by the OECD in 1983. It is based on the concept of causality which implies that human activities (and natural phenomena) exert impacts on the environment and change its quality and the quantity of natural resources. Society responds to these changes through environmental, economic and social policies. The responses form a feedback loop to reduce the pressures through human activities. According to [Shah, 2000a], these steps form part of an environmental policy cycle that includes problem perception, policy formulation, monitoring and policy evaluation.

This framework distinguishes three types of indicators: (a) indicators of environmental pressure that describe impacts from human activities on the environment, both on quality and quantity of natural resources; (b) indicators of environmental conditions (state) related to the quality of the environment and to the quality and quantity of natural resources; and (c) indicators of societal responses, measurements that show the extent to which society is responding to environmental changes and concerns [Shah, 2000a].

For example, ‘emissions of carbon dioxide’, ‘atmospheric concentration of carbon dioxide’ and ‘international climate protocols’ are examples of pressure, state and response indicators, respectively. In this case, the response is meant to reduce the pressure. In some cases, response actions can be used to improve the state of the system (for example, by removing pollutants from the atmosphere).

Leaving aside response indicators, a review of pressure and state indicators, related by means of causality in the PSR framework, shows great similarity with certain modelling approaches, in which pressure indicators are called *rates* and state indicators, *state variables*. Two of these modelling paradigms are particularly interesting for the present work: System Dynamics [Ford, 1999] and the Qualitative Process Theory [Forbus, 1984]. This similarity shall be detailed in the next section.

3 MDG Indicators of sustainable development in Brazil

A network of academic laboratories was created in Brazil to monitor the MDG. By the end of 2004, the laboratory of the University of Brasília finished a national report about the MDG7 [Salles, 2004]. Based on conceptual models [Jørgensen and Bendoricchio, 2001], these models are designed to improve understanding about environmental systems considered in the MDG7.

Models are regularly used to monitor the state of the environment in many centers, as, for example, the Dutch National Institute for Public Health and the Environment (RIVM) (Jan Bakkes[2], *pers. comm.*). It should not be surprising that pressure and state indicators in the PSR framework are functionally similar to rates and state variables in System Dynamics [Ford, 1999].

System Dynamics is a graphical version of differential equation models. The system is represented as a set of compartments (the state variables), and ‘substances’ flow between them (hence the other name for this paradigm, compartment-flow modelling). A differential equation describes the dynamics of each compartment. It is the resultant from the sum of all inflows into the compartment minus the sum of all outflows. Each flow is represented by an equation that links the rate of the flow with the values of the state variables, parameters and other variables [Robertson *et al.*, 1991]. A number of publications report the use of System Dynamics models to address sustainability problems (*cf*. [Ford, 1999]).

[1] Two frameworks derived from PSR are currently being used throughout the world: the Driving Force – State and Response paradigm, proposed by the UN Comission of Sustainable Development, and the Driving Force – State – Impact and Response framework created by the Eurpean Environmental Agency.

[2] Director of the UNEP Collaborating Centre at the RIVM, in Bilthoven, The Netherlands.

Setting the foundations for the Qualitative Process Theory, Forbus [1984] argues that the mathematical meaning of direct influences put by processes is to determine the value of the derivative of the influenced quantity. The qualitative equation *I+(A,B)* reads dA/dt = (…+B…). The mathematical meaning of a qualitative proportionality, such as *P+(C,A)* is that there is some monotonic function (f) that determines C, in a way that C = f(…A…), being dC/dA > 0.

Given the functional similarity pointed out above, it was assumed that the relation between pressure and state indicators could be represented in qualitative models based on the QPT as direct influences, for example, *I+(State, Pressure).* Accordingly, other causal dependencies included in the model were represented as proportionalities.

An example will illustrate how this approach was implemented. It draws on MDG7indicators, presented in the following table:

Table 1. Targets and indicators associated to the MDG7.

Goal 7: Ensure environmental sustainability	
Targets	**Indicators**
Target 9 – Integrate the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources	25 – Proportion of land area covered by forest 26 – Land area protected to maintain biological diversity 27 – Use of energy per unit of GDP (energy efficiency) 28 – Carbon dioxide emissions (per capita) 29 – Proportion of population that use solid fuel [Plus two figures of global atmospheric pollution: ozone depletion and the accumulation of global warming gases]
Target 10 – Halve, by 2015, the proportion of people without sustainable access to safe drinking water	30 – Proportion of population without sustainable access to an improved water source
Target 11 – By 2020, to have achieved a significant improvement in the lives of at least 100 million slum dwellers	31 – Proportion of people without access to improved sanitation 32 – Proportion of people with access to secure tenure [Urban/rural disaggregation of several of the above indicators may be relevant for monitoring towards the targets]

From Table 1, one can see that most indicators can be classified as state indicators, except indicators 26 and 28. The former is a response indicator, given that legal protection is a response against destruction of biodiversity. The latter is a pressure indicator, given that it represents the amount of gas added to the atmosphere in a certain period of time, that is, a rate.

Suppose we want to build a conceptual model about a system that includes the indicator 25, land covered by natural vegetation. It is a state (S) indicator, and the obvious pressure (P) on it is deforestation. Assuming the QPT approach to this relation, it could be modelled as

I–(land with vegetation, deforestation rate)

This relation indicates that a certain amount of natural cover is being lost over a certain period of time. This amount (*deforestation rate*) is subtracted from the quantity *land with vegetation*, yielding the new area covered by the vegetation.

Indicator 26 can be seen as a response (R) indicator. However, how does it relate to P and S indicators already mentioned? In fact, defining areas for biodiversity protection is a way of reducing deforestation. It makes sense because natural vegetation is the biggest stock of biological diversity.

P–(deforestation rate, area for biodiversity)
This relation reads as follows. There is a (unknown) monotonic function relating the protected area and the deforestation rate. This function is unknown, but it can be said that when the area for biodiversity is increasing (that is, its derivative is positive), then the deforestation rate is decreasing (that is, its derivative takes a negative sign).

The conceptual model on this topic, presented in the Brazilian national report on MDG7 [Salles, 2004], was implemented in the qualitative simulator GARP [Bredeweg, 1992] and is discussed in details in the next section.

Each of the 10 indicators mentioned in Table 1, was included in, at least, one conceptual model. This way, the indicador is contextualized in a system in which it is related to other quantities by means of causal relations. These conceptual models surprised a number of people who have read the report. They had new insights and their understanding of the problems allegedly increased.

The conceptual model about the indicator 27 (Table 1) illustrates how information is lost when two or more quantities are aggregated into a single indicator. Energetic efficiency is defined as the ratio between the amount of energy consumed during a certain time and the GDP produced during this period. The idea is that the country is more efficient in the use of energy when either more wealth is produced with the same amount of or less energy, or the same amount of wealth is produced with less energy. It may not be intuitive, but increased efficiency results in smaller numerical values of the indicator. However, often both energy consumption and GDP are increasing, what makes the situation more complex. Dealing with numbers, once the ratio is calculated there is only one number (the value of the indicator), and it is no longer possible to know why the final value has changed (whether it happened due to changes in one or in both components). We argue that a separate analysis of the two components, as it is done in the conceptual model, allows for a better interpretation of this indicator. For example, energetic efficiency may be modelled as follows:

P+(energetic efficiency, consumed energy)
P–(energetic efficiency, GDP)

According to this model, the value of the indicator energetic efficiency decreases when GDP increases faster than the consumed energy or the increase in the latter is slower than the former's increase. The difference in the velocity may be detected by means of a graphical representation of the two components. A faster increase results in a more steep line. The question then is to know if the difference in the angle of the two lines is statistically significant. In the Brazilian case, a slight numerical increase of the indicator was found over the last 10 years, leading to the conclusion that the country became less efficient. However, the statistical analysis showed that the difference was not significant, and therefore the data were not conclusive [Salles, 2004].

4 The model and simulations

The 'deforestation' model was built in the modelling environment HOMER [Bessa Machado and Bredeweg, 2002], run in the qualitative simulator GARP [Bredeweg, 1992] and the simulations were inspected with the visualization tool VisiGarp [Bower and Bredeweg, 2001].

We took the compositional modelling approach for building this model [Falkenhainer and Forbus, 1991]. This way, basic knowledge units are implemented in a library of partial models, called model fragments (MF). These MF are automatically (re)combined by GARP to create different and more complex simulation models. Actually the set of MF that forms the running model may change during a simulation, representing changes in the system structure, if they happen.

The model consists of four entities: human, land, vegetation, water. All entities are related to the others, in order to represent that human society depends on all of them. Associated with the entity vegetation are the quantities deforestation rate, regeneration rate, land_no_vegetation, land_with_vegetation and biodiversity. The entity Land is associated with the quantities erosion rate, removed_soil and agricultural production. The entity water is associated to the quantities water reserves and uses of water, and the quantities technological products, population without water and gdp are associated to the entity human. The rationale for using these quantities and their qualitative values are presented in Table 2.

The model consists of 16 MF, being 5 MF to represent three processes (deforestation, erosion and regeneration) and 11 MF to describe static aspects of the system. Three basic assumptions are defined in order to organize the simulations: *active deforestation*, *controlled deforestation*, and *active regeneration*. The main features of all the MF are the following:

MF Land and vegetation = it defines the association between land covered with natural vegetation and land without vegetation cover. Obviously when deforestation occurs, the former immediately changes into the latter condition. This situation is modelled by means of two quantities: *land_with_vegetation* and *land_no_vegetation*. There is an inverse correspondence between their values, so that they always appear in pairs: zero/max; large/small; medium/medium; large/small and max/zero.

Table 2. Quantities included in the model.

Rationale for including the quantity	Quantity	QS
Defined as the rhythm of natural vegetation removal	deforestation rate	{zp}
Defined as the rhythm of the vegetation regeneration	regeneration rate	{zp}
It is the rhythm of soil removal, speed up by deforestation	erosion rate	{zp}
In its natural state, land is covered by vegetation	land_with_vegetation	{zsmlm}
Area where natural vegetation was removed by deforestation process	land_no_vegetation	{zsmlm}
Biological diversity, considered as the diversity of species, populations and ecosystems; it is related to the natural vegetation cover	biodiversity	{zsmlm}
Products coming from multiple agricultural uses of the land	agricultural production	{zsmlm}
Soil removed as a consequence of the erosion process, being lost organic matter and nutrients	removed_soil	{zsmlm}
In this model, technological innovations (food, raw material and medicine) related to the use of biodiversity	technological products	{zsmlm}
Water reserves include river, lakes and springs	water reserves	{zsmlm}
Possibility of using water in different human activities, related to water availability	uses of water	{zsmlm}
Proportion of the population without access to safe water supply	population without_water	{zsmlm}
The gross domestic product, used as an indicator of the wealth of a country or a region	gdp	{zsmlm}

{zp} is QS = {zero, plus}; {zsmlm} is QS = {zero, small, medium, large, max}

MF Deforestation = the process is represented by means of two direct influences posed by the deforestation rate. A negative influence determines the reduction in the area covered by natural vegetation, and a positive influence causes the increase of the deforestated area:

I–(land_with_vegetation, deforestation rate)
I+(land_no_vegetation, deforestation rate)

In order to handle assumptions for defining different scenarios, this MF has two 'child' MF, Deforestation active (associated to the assumption *active deforestation*) and Deforestation controlled (associated to the assumption *controlled deforestation*). In the former, *deforestation rate* has value plus and, in the latter, zero.

MF Regeneration = an opposite effect is caused by the regeneration process. It is modelled as direct influences of the *regeneration rate* on the area of land with and without natural vegetation. This MF is associated to the active regeneration assumption:

I+(land_with_vegetation, regeneration rate)
I–(land_no_vegetation, regeneration rate).

MF Land and erosion = defines the existence of removed soil.

MF Vegetation and erosion = it takes as input the MF Land and vegetation, and creates a dependence relation between the quantities land_with_vegetation and land_no_vegetation with erosion rate modelled by means of qualitative proportionalities:

P+(erosion rate, land_no_vegetation)
P–(erosion rate, land_with_vegetation)

MF Erosion = the erosion process is defined in this MF as a mechanism in which the rate puts a direct influence on the quantity of soil that is removed:

I+(removed soil, erosion rate)

MF Agriculture = this MF captures the effects of erosion on the agricultural production. It is assumed that there is an inverse and directed correspondence between the amount of removed soil and production, modelled by means of a qualitative proportionality, so that when removed soil increases, agricultural production decreases:

P–(agricultural production, removed soil)

MF Water reserves = Another effect of erosion is the loss of water resources. The MF establishes a relation between the amount of water in the reservoires and the soil removed by the erosion process. Here there is an inverse and directed correspondence between the values of water and soil removed. The dependence is captured by means of a qualitative proportionality:

P–(water reserves, removed soil)

MF Water usage = This MF takes as condition the MF Water reserves being active and represents the relation between water availability and uses of water. This relation is captured by means of a proportionality, so that when the water reserves change (increase or decrease) the use of water changes in the same direction, and by a correspondence between the use and the amount of water available:

P+(uses of water, water reserves)

MF Water for humans = it represents the use of water for human consumption. It is assumed that the population supplied is proportional to the water available for different uses. However, in line with the MDG, we included in the model a quantity representing the population that does not have access to safe water. This dependency is then captured by a negative proportionality so that when the water available for human use decreases, increases the amount of people without safe water:

P–(population without water, uses of water)

Another group of MF explores the effects of deforestation on biodiversity and technological uses of genetic resources.

MF Vegetation and biodiversity =. in this MF we assume that biodiversity is directly related to the area covered by natural vegetation. Thus, increases in the area with no cover imply loss of biodiversity. These dependencies are captured by the proportionalities:

P–(biodiversity, land_no_vegetation)
P+(biodiversity, land_with_vegetation)

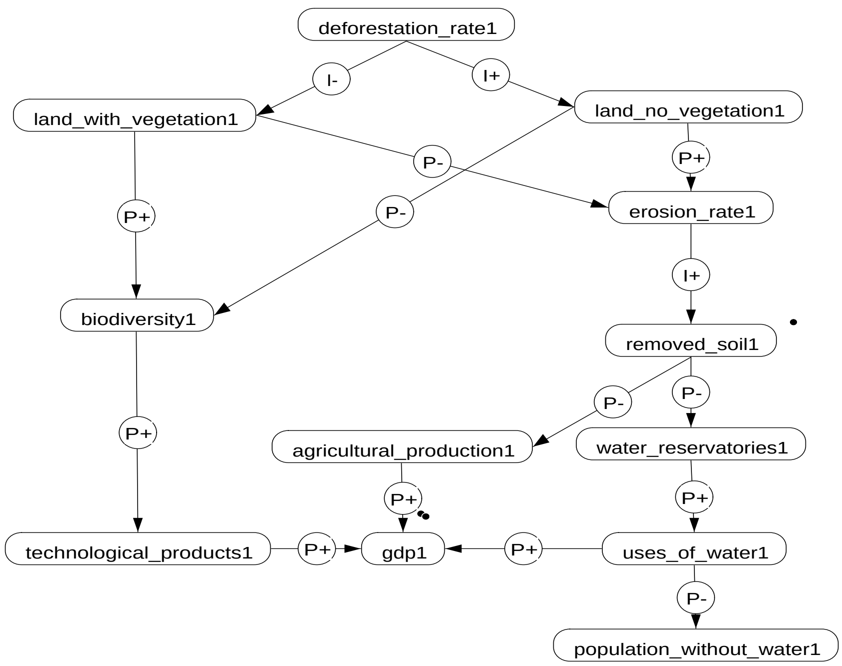
MF Biodiversity and technology = innovative products exploring genetic resources are in the front line of development. This MF creates a relation between biodiversity and technological products via a positive proportionality. This dependence indicates that loss of biodiversity leads to less technological products:
P+(technological products, biodiversity)

MF Influences on GDP = the final result of the causal chain expressed in this model are the changes in the level of poverty, represented in the model by the quantity *gdp*. It is assumed that the behaviour of this quantity is the resultant of influences coming from three sources: agriculture, biotechnology and water resources. These forces are represented by the following set of proportionalities:

P+(gdp, technological products)
P+(gdp, agricultural production)
P+(gdp, uses of water)

The causal model, as shown in a VisiGarp screen shot, is presented in Figure 1.

Figure 1. Causal relations in the 'deforestation' model.



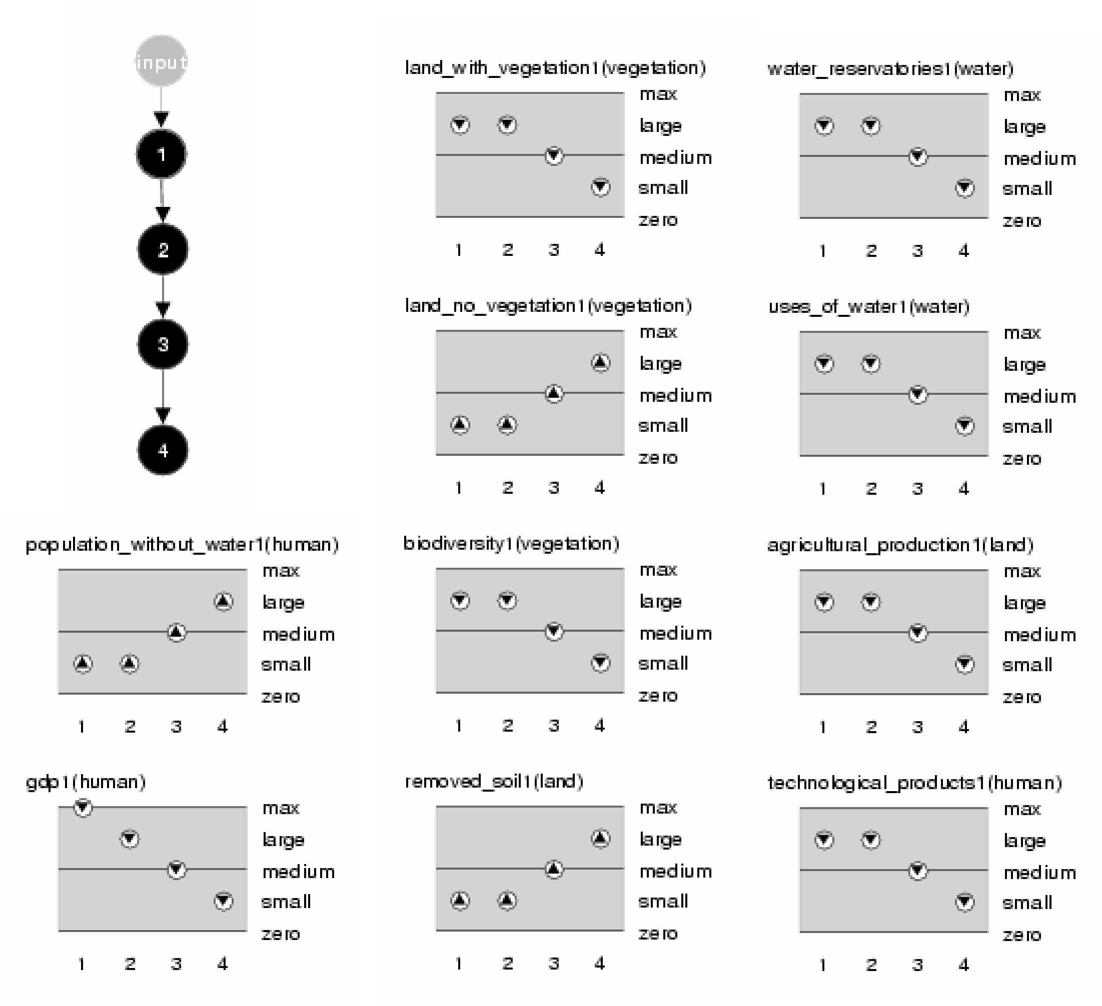
We describe here a complete simulation of the effects of the deforestation to illustrate the potential of the model.

The initial scenario includes the following quantities and respective values:

[land_with_vegetation <large, ?>]; [land_no_vegetation <small, ?>]; [removed soil <small, ?>]; [agricultural production <large, ?>]; [uses of water <large, ?>]; [technological product <large, ?>];
[gdp <max, ?>].

The simulation produces four states, in which increase the values of population without safe water and decreases the value of GDP. Figure 2 below presentes the behaviour graph and the value history of these quantities.

Figure 2. Behaviour graph and value history of relevant quantities in a simulation of the effects of deforestation.



5 Discussion and final remarks

The use of qualitative reasoning techniques to model the indicators of MDG7 was proven to be a success. The Brazilian national report produced at the University of Brasília was welcomed as innovative, clear and didactic. Representing complex issues related to environmental sustainability as diagrams captures a systemic view; and integrating different indicators by means of causal dependencies allows for a representation of the dynamics of the system. This way, reading the report on MDG7 it is possible to explain why certain indicators must change in a particular direction when others are changing. This qualitative approach proved to be useful to reason about the progress towards the targets set in the MDG because, even in paper and pencil models, dynamics may be represented in terms of indicators increasing / decreasing. The predictions supported by these models may be refined if good quality quantitative data is available. These features are essential to improve the 'average citizen' understanding of the structure and behaviour of systems of interest.

The implementation in a qualitative simulator of a conceptual model about the consequences of deforestation included in the report of MDG7 produced interesting results. It is necessary now to have end users evaluating model and simulations, in order to check if model and simulations complexity were kept in levels that are adequate to the 'average citizen'.

Some of the modelling principles stated in [Salles and Bredeweg, 1997] were adopted in this modelling effort to achieve these results. Worth to mention are the 'one concept, one MF' principle, by which the most relevant concepts were summarized in a set of 16 MF; the 'minimum required variation' principle, adopted to reduce the amount of quantities and possible qualitative values in order to keep the balance between complexity and significance. The decision of starting modelling with 'a core of fundamental concepts', from which the library can be extended to include more complex problems, resulted in a series of initial scenarios that allow the user to explore parts of the library and run models about the direct effects of deforestation in the vegetation, in the soil, in the water resources and in poverty.

All in all, we believe that it is worth to keep exploring QR for making sense of the indicators of the MDG. The use of qualitative models improves understanding of the important issues addressed there. Ongoing work includes preparing a regional report of the eight goals for the middle center of Brazil, in which conceptual models are being built to represent social and economic indicators, and implementing the rest of conceptual models designed for the MDG7 in the qualitative simulator GARP. And, most important, testing the material with stakeholders to confirm our feeling that QR has an important role to play in achieving the MDG.

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