Integrated Assessment **2:** 123–138, 2001.

Integration of case studies on Global Change by means of qualitative differential equations

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Received 27 April 2000; revised 6 December 2000

We present a novel methodology to integrate qualitative knowledge from different case studies on Global Change related issues into a single framework. The method is based on the concept of qualitative differential equations (QDEs) which represents a mathematically well-defined approach to investigate classes of ordinary differential equations (ODEs) used in conventional modeling exercises. These classes are defined by common qualitative features, e.g., monotonicity, signs, etc. Using the QSIM-algorithm it is possible to derive the set of possible solutions of all ODEs in the class. By this one can formulate a common, qualitatively specified cause–effect scheme valid for all case studies. The scheme is validated by testing it against the actually observed histories in the study regions with respect to their reconstruction by the corresponding QDE. The method is outlined theoretically and exemplary applied to the problem of land-use changes due to smallholder agriculture in developing countries. It is shown that the seven case-studies used can be described by a single cause–effect scheme which thus constitutes a *pattern of Global Change*. As a generally valid prerequisite for sustainability of this kind of land-use the presence of wage labor is shown to represent a decisive factor.

Keywords: case study integration, integrated qualitative modelling, land use change, smallholder agriculture, soil degradation

1. Introduction: Integrating what and what for?

In recent years a vast number of studies, models and assessments of Global Change and related issues had been carried out which are attributed by the term "integrated". Dominating are various modeling attempts that among others differ in

- the level of analysis, i.e., aggregated, parameterized descriptions (e.g., [1]) versus detailed, functional oriented approaches (e.g., [2]),
- the relation to normative aspects of global environmental change, reflected, e.g., in the differentiation between policy evaluation and policy optimization models [3],
- the degree to which policy makers or stakeholders are participating in the model building and application process (e.g., [4]) or
- the spatial resolution and explicitness, varying from zero-dimensional global approaches [5] to highly resolved regional approaches [6].

Furthermore, there are approaches which are framed by a focused process rather than a model (e.g., [7,8]). All these approaches start off with a specific problem on hand and with the insight that *the interaction of the elements and facets contributing to the problem brings about essential features which cannot be understood if just summing up properties of the single elements*. Thus the first goal of integration is to find out, what particular dynamical features of Global Change have to be considered as emerging effects due to the complex interactions involved [9].

The emergence of these effects bear some important implications for policy making: there hardly will be a single steering wheel which just has to be turned into the right direction in order to achieve a correction of the course towards ever more endangering environmental changes. In other words, it is the general task of integrated approaches to Global Change to overcome mono-causal views like: Coca-Cola destroys the world, so we have to get rid of Coca-Cola to save the world.

Though being entitled as *Global* Change some care has to be taken concerning the involvement of regional or local processes and elements. Against this background, the notion of *systematic* vs. *cumulative* changes is helpful [10,11]. Whereas the first comprises aspects of Global Change that are mainly governed by global processes, e.g., global climate change, the reduction of the ozone layer or "economic globalization", the second includes aspects which receive their global relevance by their parallel occurrence in many different regions on the globe. The intercontinental or even global couplings between these occurrences can be considered as of secondary importance compared to the relevance of the local dynamics. Examples include the worldwide soil degradation [12,13] or the shortage of freshwater [14].

From this ideal picture of systematic and cumulative changes and against the background of the dichotomies of the approaches listed above, some important questions and problems for the different integrated approaches transpire. If local processes are important, how do we take care of these peculiarities when heading for the global picture and global strategies? What can we learn from studies and experiences earned in one region when searching for problems and solutions in another region? Do we need some kind of an atomistic approach which treats each single subject in each single region in a unique way? Is there a limited set of rules and mechanisms governing the dynamics of Global Change? What properties of the elements are important to understand the effects emerging from complexity in the overall dynamics? Are there dynamical properties of Global Change, e.g., irreversibility, which, if related to a consensually problematic interference between humankind and nature, would quite evidently be considered as non-sustainable? Or is it purely a question of political decision what has to be seen as problematic?

2. Hypotheses

The present paper deals with a methodology created to give answers to some of the questions raised in the last section. The method is based on the concept of qualitative differential equations (QDEs) which had been developed in the field of so-called Artificial Intelligence [15,16]. For the following hypotheses some evidence will be given in the present paper:

1. The interplay between local, regional and global facets of Global Change can be organized into a set of patterns of civilization–nature interactions. By using the idea of patterns, local peculiarities have to be aggregated to form specific constellations of functional properties of the processes of Global Change. Consider, for example, two regions where due to social and natural circumstances an intensification of agricultural land-use is related to an increase of soil degradation. In contrast, in a third region the circumstances and the way, how intensification is achieved lead to a released pressure on the natural resources. Then one might group the first two regions into one and the last into another pattern. The pattern approach is thus located in *between* the unachievable atomistic approach and the oversimplifying mono-causal approach.

2. In view of the uncertainties in the knowledge of the processes considered to be relevant for global change and the often inherently qualitative character of the relationships, it is rather tempting to develop conceptual models using simple *quantitative relationships* to represent this vague knowledge [17,18]. Yet, if these models get more and more complicated it becomes increasingly difficult to distinguish whether derived features are due to some model-based artifacts or whether they should have some real correspondences. We will show that there is a powerful *qualitative modeling* approach which avoids the somewhat arbitrary representation of vague knowledge by quantitative equations. In this way it is possible to analyze emerging qualitative features of the entire system by qualitative methods based on the knowledge actually available.

3. Local features can be "hidden" within the qualitative relationship. Consider, for example, the impact of agricultural intensification on soil degradation already mentioned above. Then it might well be the case that in one region it is reasonable to speak about a logarithmic relationship, whereas another region might exhibit a quadratic relation between the appropriate variables. The qualitative relations used in the methodology presented use a common property of both relations: soil degradation is a monotonously increasing function of agricultural intensity. In specifying a set of these qualitative relationships we get a model which generalizes the mechanisms considered in different regions into a single model. We will show how to use case studies from different regions as the basic information tool to specify the relations as well as to provide an empirical baseline for validation (in the sense of non-falsification) of the model.

4. The uniqueness of the solution of a quantitative model has to be sacrificed to the sole use of qualitative information, i.e., an entire set of behaviors exists rather than a single one. Within this set of possible behaviors it might be possible to identify a, let us call it, "non-sustainable" subset, i.e., those behaviors which by their common properties can be identified as damaging human development on the long term. If there is, for example, a solution where environmental pollution is increasing once and forever, we might well evaluate this evolution as intolerable (see also [19]).

So far, the method has been applied within the so-called Syndrome-Approach [14,20–22]. Yet the method is not restricted to this concept and recently has also be applied for a case study integration exercise within the DFG-Special Program "Man and Global Environmental Change" [23]. This latter extension of the Syndrome-Approach represents also the basic heart of the present paper.

3. Qualitative differential equations

In this section we want to describe the general features of the mathematical tool underlying our methodology. We want to do so along a simple example instead of giving detailed mathematical information, which can be found in the respective literature [16,24]. The example we are going to use is taken from the field of theoretical ecology, in particular population dynamics [25] and extended by a simple management component.

In quantitative terms, logistic growth for a population P is usually described by a differential equation of the form

$$G = \frac{\mathrm{d}P}{\mathrm{d}t} = \alpha P(P_\mathrm{m} - P) \qquad (1)$$

with a rate coefficient α, a climax population P_m and a maximal growth rate $G_\mathrm{m} = (\alpha P_\mathrm{m}^2)/4$ corresponding to a population $P_0 = P_\mathrm{m}/2$. The growth rate exhibits an inverted U-shape function in dependency of the population P, shown

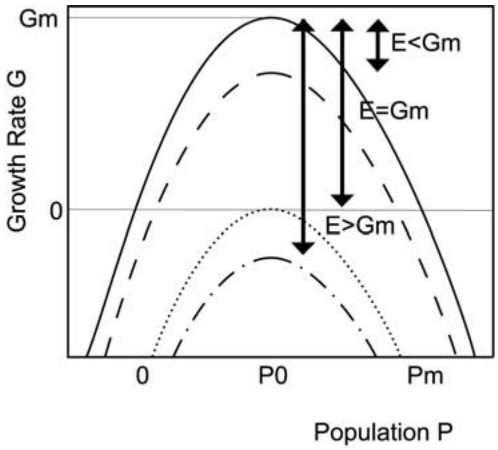

Figure 1. Basic relation for the didactic model to explain the qualitative modeling approach. If subject to a constant withdrawal E, the U-shaped relation between the population P and the growth rate G gives rise to three different types of behavior. Starting from the climax state $P = Pm$, the population either stabilizes at a level beyond $P0$, if the withdrawal is less than Gm (dashed line) or right at $P0$ if $E = Gm$ (dotted line). In case of $E > Gm$, the population finally vanishes (dash-dotted line).

as the solid line in figure 1. If we would start with a small population P_1 the growth law in equation (1) would finally lead to the climax state P_m with the typical S-shaped logistic growth over time. This is a stable equilibrium, i.e., the system stays there forever.

In a second step we introduce some external perturbations to the system in form of a constant withdrawal E, i.e., the new growth rate is $G' = G - E$. In figure 1 the resulting growth rate for three different values of E is shown:

- $E < G_m$ (dashed line): the stable equilibrium is shifted towards values of P smaller than P_m, i.e., $P'_m < P_m$. If we start with the old climax state the population would slowly decrease till it reaches its new equilibrium value P'_m.
- $E = G_m$ (dotted line): the equilibrium is now right at $P''_m = P_0 = P_m/2$, i.e., the withdrawal E is equal to the maximal growth of the unperturbed system. This case is often referred to as *maximal sustainable yield* and represents a saddle point, as for perturbations less than zero the equilibrium is unstable. Again an initial state in the unperturbed climax would lead to a decreasing population ending at half of its original value.
- $E > G_m$ (dash-dotted line): now the withdrawal is too large. No equilibrium exists, i.e. the species finally will be extinct.

The dynamical behaviors of the system depend on the actual values for the parameters α and P_m as well as the magnitude of E, but it seems that the structure of three different behavior classes is a general property of logistic growth. Therefore these properties should be obtained by a purely qualitative description as well which actually would *prove that the existence of three types of solutions is a general feature*. The concept of qualitative differential equations and its implementation within the QSIM-package developed at the University of Texas, Austin, allows representing the logistic growth in a more general way.

In the first step the relevant variables are characterized by so-called *landmark-values*, i.e., values where some kind of qualitative change in the relations between this specific variable and other system elements are assumed to take place. Taking the variable population from the example above, these values are 0, P_0 and P_m with $0 < P_0 < P_m$. It is important to stress that for the analysis by qualitative differential equations it is not necessary to know the actual values of these landmark-values, but just their existence and relative order. For the growth rate G_m the landmark-values are 0 and $G_m > 0$.

Its magnitude and its direction of change constitute the qualitative value of a variable. The magnitude is given either by a landmark-value or by an open interval between two adjacent landmark values. The direction of change is either specified as positive (encoded by ↑), steady (°) or negative (↓). In this way a decreasing population between P_0 and P_m would be written as $[(P0, Pm), \downarrow]$. A specific qualitative state is then given by the combination of the qualitative values of all variables.

Within the second step of formulating the qualitative model, the relations between the variables are specified in terms of *constraints*. In case of the logistic growth one can make use of the so-called U-constraint:

$$((\mathtt{U-}\ \mathtt{P}\ \mathtt{G}\ (\mathtt{P}_0\ \mathtt{G}_m))\ (\mathtt{0}\ \mathtt{0})\ (\mathtt{P}_m\ \mathtt{0})). \qquad (2)$$

This constraint states: for populations below P_0 the growth rate G is a monotonously increasing function of P, for values of P above P_0 it is a monotonously decreasing function. At $P = P_0$ the value of G is equal to G_m. Furthermore, for $P = 0$ and $P = P_m$ the growth rate is zero. This corresponds to a general formulation of the U-shaped relation sketched in figure 1. The syntax used in (2) is the one also implemented in the QSIM-software package. By specifying all the relations in this way, e.g., also for the relation between the withdrawal E, the natural growth rate G, and the net-growth rate NGR, i.e. `((ADD NGR E G))`, one can easily use the package to obtain all the solutions compatible with these constraints, i.e., the usage and application of the QDE-concept is rather straightforward and does not require a lot of programming skill. It is important to note that the algorithm does not use any numbers, but is implemented by purely symbolic manipulation. For the full model code see appendix A.

What do results look like and how are they interpreted? As an output of the simulation the package provides two types of graphs: a behavior tree and qualitative time plots (figure 2):

- The behavior tree for the didactic example is shown in figure 2(a). Each symbol represents a different qualitative state. Starting from the single state on the left (filled circle), given by the system in its unperturbed climax population, it should be read as follows: there is a initial time interval $(T0, T1)$ where a unique behavior arises (open

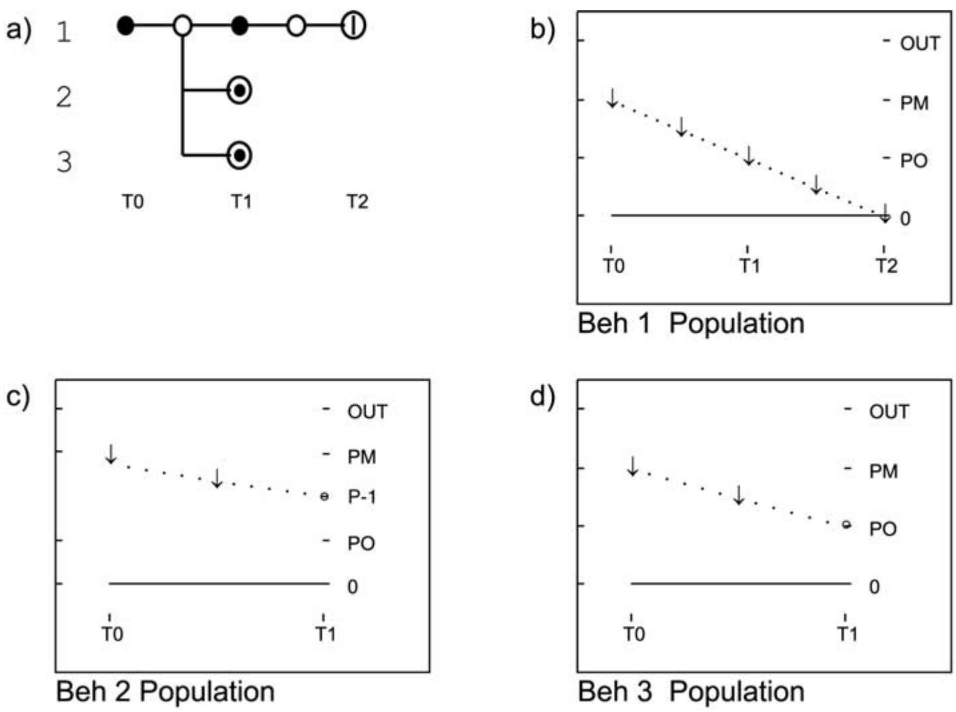

Figure 2. Behavior tree (a) and qualitative behaviors (b)–(d) for the variable "Population" of the simple didactic model for a general logistic growth of the population dynamics. Note that in figure 2(c) a new landmark is introduced by QSIM itself, denoting the final value of the population at time $T1$. Further discussion see in text.

circle). Then at a time $T1$ three different events can occur, corresponding to the split up into three different behaviors. Two of these behaviors (numbered 2 and 3) are eventually truncated by reaching an equilibrium state (encoded by the truncating symbol ⊙), whereas the truncating symbol ⦶ at solution 1 indicates that the behavior leaves the regime for which the model is defined to be valid.

In conclusion it is seen that there are three different behaviors that are compatible with the qualitative constraints for the relations between the systems elements. This is in complete agreement with the expectations and the results from the quantitative exercise outlined above. By introducing a landmark value E_{m} for the withdrawal and relating this value to G_{m} in specifying the net-growth to be zero whenever $E = E_{\mathrm{m}}$ and $G = G_{\mathrm{m}}$, we are even able to relate the three solutions with the magnitude of E in relation to E_{m}. For $E > E_{\mathrm{m}}$, $E = E_{\mathrm{m}}$, and $E < E_{\mathrm{m}}$ we obtain behaviors 1, 2, and 3, respectively. This feature is not represented in the solution graphs in figure 2 for sake of simplicity of illustration.

- In order to give insight into the internal structure of each possible behavior the program provides qualitative time plots. Figure 2(b) shows the time plot for the variable P for behavior 1. On the x-axis one finds the time scale, specified by time points $T0$, $T1$ and $T2$. On the y-axis the landmark-values as discussed above are marked. Population at time $T0$ is then depicted by the symbol ↓ at the landmark P_{m}. That is, the magnitude is equal to P_{m} and decreasing. Consequently in the time interval $(T0, T1)$ the magnitude is "somewhere" in the interval (P_0, P_{m}) and still decreasing. This is again indicated by the symbol ↓, now drawn between P_0 and P_{m}. In this manner the encoding of the solution continues: at time $T1$ the landmark P_0 is reached and population still decreases. Finally at time $T2$ the population vanishes and is, according to the model, still decreasing. The behavior leaves the regime for which the model is defined, as mathematically the next state would have a negative population. In conclusion behavior 1 exactly corresponds to the case $E > G_{\mathrm{m}}$ in the quantitative case: the withdrawal is too large, henceforth population does finally vanish.

  It should be stressed that within this modeling concept time is a qualitative variable only. The time *points* $T0, T1, \ldots$ are given by single events, i.e., at least one variable takes on a landmark-value. Thus time is not given explicitly in terms of hours, days or seconds, but in terms of events and intervals in between. In the example just given the time points $T0$, $T1$ and $T2$ are given by the events $P = P_{\mathrm{m}}$, $P = P_0$ and $P = 0$, respectively. The two other behaviors are depicted in figures 2(c) and (d). It can be seen that they reconstruct the expectations, as both reach equilibrium with a direction of change in P equal to zero (symbol ∘). One of these solutions achieves a final population larger than P_0, in the other solution the equilibrium population is equal to P_0.

Table 1 summarizes the properties of the qualitative modeling approach by QDEs in comparison with conventional modeling by ordinary differential equations.

What do we learn from this kind of qualitative modeling exercise? First of all, we learn that *any* specific U-shaped

Table 1
Comparison of important features of conventional modeling with ordinary differential equations (left) and qualitative modeling (right) using QDEs.

Conventional modeling	Qualitative modeling by QDEs
Numbers on the real axis	• Landmark values specifying distinct values where relations to other variables change qualitatively, e.g., Bo (see below). • Values to be taken by the variable: landmarks and intervals in between together with the direction of change (↑, ↓, or °).
Real valued functions modeling the interrelation between the different variables	Qualitative features only, e.g., A is monotonically increasing with B, A is "U-shaped" in B with Bo as turning point, etc.
System of differential equations	Corresponding number of qualitative "constraints" relating state variables and their changes.
Single solution explicit in time	Entire solution tree of *all* possible solutions compatible with the constraints. Time as a qualitative variable, specified in terms of events of qualitative system changes.

function with a top-sided vertex relating population P and its growth rate G brings about one of the three possible behaviors. It thus might be concluded that the observation of one behavior in Region 1 and of another behavior in Region 2 might well be due to the same qualitative properties of the mechanisms behind the observations. This addresses the issue of patterns of interactions and of regional similarities in terms of functional properties.

Secondly, we learn from the structure that the event at time $T1$ uniquely determines the final outcome. For example, if at $P = P_0$ the population is still decreasing it is going to vanish in any case – assuming that the structure does not change and no external action is taken. This is a dynamical property as discussed in section 1 and if it would be used to describe a real system it might be called unsustainable by rather general properties.

4. Integrating case studies on Global Change: The outline

In the following we want to show how this modeling technique can be used within Global Change Research to address some of the issues raised above. To take a concrete example we will consider the question of land-use changes, particularly due to smallholders' agriculture in developing countries. Land-use changes in general are considered to be a major element of Global Environmental Change, as they are related to, e.g., emissions of greenhouse gases, soil degradation, loss of biodiversity or shortening of freshwater resources [26,27]. In facing the issues raised above it was concluded that

> Modelling the dynamics of land-use and land-cover change has been hindered by large variations of those dynamics in different physical settings. Global aggregate assessments based on simple assumptions miss the target for large sections of the world, while local and regional assessments are too specific to be extrapolated to wider scales [26, p. 12].

Against this background the basic idea of our approach, i.e., to use patterns of civilization-nature interaction together with the modeling approach sketched in the previous section, comes into play. *For regions with the same qualitative properties of the relevant mechanisms a single qualitative model can be used to describe the dynamics of land-use and land-cover change.*

From this the question emerges, how we find out whether these mechanisms are (a) relevant and (b) equal in terms of "quality" as defined by the modeling scheme. The basic idea is to start from a variety of case studies as the major information base and to perform the steps sketched in figure 3, discussed in the following and exemplified in the next section.

1. Without a few exceptions (e.g., [28]) case studies though investigating similar issues use different definitions, variables and methods. This is why it is so difficult to compare them and to draw integrating conclusions from a comparison. This difficulty can be overcome by formulating a common, higher-level vocabulary, capable to integrate the specific definitions in each study. Taking the ecological example from above, one study might investigate the population dynamics of mice, whereas another one is concerned with the dynamics of a small ecosystem. By *variable abstraction* we can integrate both aspects into the higher-level variable "biomass". The reason why we can do so is that in both cases it appears to be reasonable to assume the U-shaped relationship with the respective growth rate.
2. In the second step the case studies and if necessary some further information, e.g., quantitative data, interviews with experts or local actors, are used to obtain the *qualitative time behaviors* for the abstracted variables in the different case study regions. This step corresponds to the data acquisition phase in conventional modeling exercises. The advantage, however, is, that the method outlined here can make use of qualitative information: "the opening of forests by logging companies in the 1980s led to a rapid increase of paddy fields" [29]. Clauses like this one can directly be formalized in terms of qualitative time plots as the ones in figures 2(b)–(d). In many cases the result of this step will not be unique, as the information given is not complete. Therefore, care has to be taken in order to cover all the possible time behaviors compatible with the information available. Of course, it is also possible to translate existing quantitative time series into qualitative plots.[1]

[1] There are some first, promising attempts to combine qualitative and quan-

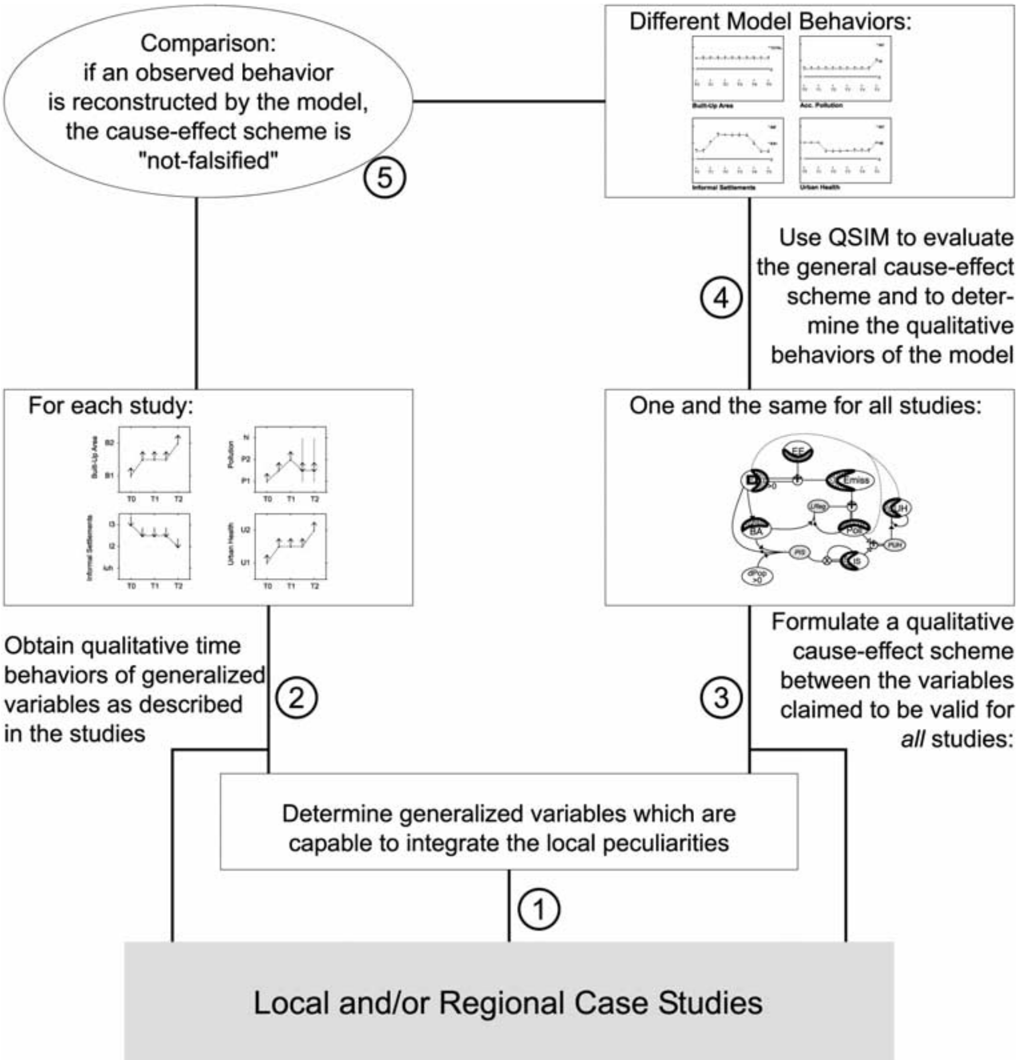

Figure 3. Case-study integration scheme.

3. In the third step the actual *modeling* is performed, i.e., based on the case studies and further, sometimes theory based information, a cause–effect scheme between the generalized variables is formulated. This scheme is claimed to be valid for all the case studies considered and is formalized using the syntax of qualitative differential equations. There are different ways to achieve this goal: one might start off with a cause–effect scheme for *each single study* and try to integrate it afterwards. The other option is directly to formulate this network of interrelation and to give some evidence for each relation from the studies. As in conventional modeling exercises, it is basically up to the developer to decide on the method.

4. Using the QSIM-algorithm all time behaviors compatible with the cause–effect scheme formulated in step 3 are derived. It might well be the case, in particular within the first exercises with the technique, that the number of solutions is very large and thus the behavior tree appears to be "intractable". The reasons can be divided into "substantial" and "technical" ones. Whereas the latter can be removed by some "tricks" within the algorithm [24], the first are more serious as they directly relate to an insufficient specification of the model or to a high degree of complexity which in case of ergodic systems is proven to lead to arbitrary sequences of qualitative states [32].

Consider for example the Cobb–Douglas production function often used in economic modeling. In quantitative terms this function reads as $E = \eta K^{\gamma} L^{1-\gamma}$ where η is the total factor productivity, K is the capital stock, L is the labor force and γ is the substitution elasticity between capital and labor. Using the qualitative calculus of QSIM, we would have to use the multiplication constraint, i.e., `((MULT K L E))`. Now assume that we have an increase in capital and a decrease in labor force. Then the qualitative constraint used here would not allow determining the direction of change for the economic output E, i.e., it might be increasing, decreasing or even constant. This is due to the fact that there is no specifica-

titative modeling approaches and thus to use the level of information which actually is available [30,31]. For sake of clarity we restrict ourselves to the presentation of the purely qualitative case.

Table 2
Regions and major issues of the case studies in Lohnert and Geist [35], here serving as an information base for the exemplary application of the integration method.

Region	Major issues
Upland Area in Nepal	Pastoralism; collection of wood and forest products for subsistence use as well as for market sale (illegal, but tolerated); commuting for work and market in nearby towns; subsistence can hardly be found as single source of income.
Laotian Forests	Forest clearing by international companies; development of large water management schemes (Mekong) promoted by international development agencies; shift of production techniques in small villages towards lowland rice field cultivation.
Eastern Cape Province	Homeland of illegal dwellers in informal settlements in Cape Town (late 1980s); outmigration due to marginalization with an increasing need to cultivate unsuitable land, causing soil erosion and an increasing destruction of the resource base.
Miombo Highlands, East Africa	Tobacco cultivation as the major source of income; pressure on environment is direct (soil erosion) and indirect by need of wood for curing; smallholders have their own farms, but are also working on largeholder's estates.
Rural Botswana	Governmental drought relief programs including the provision of off-farm labor, e.g., infrastructure construction and support to weaken the urban-rural area link. Efforts to support lying fallow unsuitable lands during droughts.
Atlantic Rainforest, Brazil	Favorable climatic conditions with major limitations on soil fertility; two villages: Bela Vista with a rapid decline of natural resource due to slash-and-burn agriculture and Dois Irmãos with workplaces on leisure farms of rich Sao Paoloeans.
Dominican Republic	Charcoal burners: collecting wood, processing and selling on nearby markets; GTZ-supported program, e.g., to collect dead wood only instead of green wood. "Personal" view of people still hints to attitudes of disadvantage compared to farmers.

tion of the elasticity or information whether the increase in K or the decrease in L dominates. Thus, in order to avoid the corresponding branching of the behavior tree it would be necessary to install further constraints concerning the changes in L and K. These constraints might then also include some information on the elasticity γ.

5. In the final step it has to be checked whether the model reconstructs the observed qualitative behaviors. In comparison to conventional modeling exercises this corresponds to the validation of the model. A further criterion for the quality of the model is the total number of behaviors. If this number is very large, the function of the qualitative model as a filter is not very good, i.e., there is a danger that the model produces behaviors which never will have real analogues (see the discussion at step 4). In any case, if the qualitative model could reconstruct the behaviors observed, the applicability of the cause–effect scheme can be considered as not falsified. This non-falsification, however, is the most one can expect from any kind of analysis, i.e., it cannot be excluded that the actual mechanisms are different to those implemented in the model. This, of course, also applies to conventional approaches which actually is obvious in the multitude of models used, e.g., for climate projections. Note, however, that compared to conventional modeling attempts, the reconstruction in terms of qualitative behaviors is always exact and does not rest on statistical grounds.

As a matter of fact these steps hardly will be performed in exactly this order. Instead, an iterative procedure will be carried out, i.e., after a first complete cycle, the model will be revised and if this does not suffice even the variable abstraction step (1) might be reconsidered. At the end of the procedure, however, a sufficiently good qualitative model should have emerged which represents a common network of interrelations for the case studies considered. If globally relevant this network can be considered as a major *pattern of civilization-nature interaction.*

5. Case study integration: An example

Let us now turn to a concrete example, how to apply the methodology and what to learn from it. As mentioned above we want to focus on smallholders' agriculture in developing countries. There are many case studies on this subject (e.g., [28,33–35]). Work is in progress to formulate a broadly integrating cause–effect scheme and the example given here covers only a small part of all these studies, i.e., those in the book by Lohnert and Geist [35] (see also the contribution from Petschel-Held et al. therein). These studies concentrate on the smallholders' *coping strategies in changing environments* and have been carried out within the DFG Special Program on "Man and Global Environmental Change – Human Dimensions" within the years 1994–1999.

The regions of the case studies included here are scattered throughout the world. They include a total of 7 regions and in most cases focus a few villages considered to be representative for the entire area. Table 2 summarizes the regions and the major issues on which the respective case study concentrates.[2]

[2] The book contains two more case studies for the Andean Mountains in Argentina and for the Maazailand in Tansania. The first study focuses on anthropological and religious aspects of land-use and does not contain assessments of the natural environment. The second study focuses the conflict between Maasai herders and resettled farmers. Both aspects are not included in the present model and the studies are therefore neglected henceforth.

5.1. Generalized variables

All case studies deal with the question of how the smallholders support their daily income and how this is related to the environmental conditions around them. The major functional difference between sources of income relates to their potential impacts on this environment, i.e., whether they have a direct impact or not. Examples for the first comprise any kind of agriculture (farming, pastoralism) as well as activities in collecting and processing natural products (wood, bamboo, etc.). Income sources without a direct impact on the environment in particular include any kind of off-farm labor. It is obvious that within these general categories, differences exist between the different regions. Whereas in Nepal agriculture refers in particular to livestock farming, the same issue in the Miombo Highlands is related to tobacco plantation. In the Dominican Republic, however, it relates to none of these, but to the collection of wood and its processing to charcoal. Similar examples are of course applicable for off-farm labor, ranging from housekeeper activities in the study on the Atlantic Rainforest in Brazil to construction work in Botswana. Nevertheless, these two general categories occur in almost any study in one or the other distinction. Therefore, we use LA and LW as variables for "agricultural" and wage labor, respectively. Together with these two goes the total labor available, LT.

The "changing environment" all case studies are dealing with, can be generalized into a variable for the quality of the resource (QR) and its change. Again there are differences between the case studies, e.g., it is detailed as soil erosion (landslides) in Nepal and the Atlantic Rainforest or the loss of soil fertility in the tobacco plantations in the Miombo Highlands in East Africa and rural Botswana. In any case, QR can serve as a generalized term for all these aspects.

Similar arguments apply for the income from wage labor (IL) and the yield of the generalized agricultural activities (Y). Both variables are henceforth used in the integration exercise.

5.2. The history in the study regions

In this section the generalized variables are used to picture the historical development in the study regions in a common vocabulary. In particular the recent trends in labor allocation have to be taken care of. Attention has to be paid also to *qualitative changes in the development of the variables*, i.e., whether something has increased first and is now decreasing or vice versa. If no such change occurs the recent history is given by one single qualitative state. This fact might look confusing on the first glance, but it has to be kept in mind that a single qualitative state might well refer to an open time interval in case of no qualitative changes in between (see section 3).

If we take a closer look, lets say on the case study on the Eastern Cape Province, we can find statements like the following [36, p. 113]:

> In the rural areas of former Transkei and Ciskei the livelihood was and still is based on subsistence agriculture. However, the subsistence basis has been severely damaged due to food crop cultivation on unsuitable land and due to overgrazing. This resulted in ongoing erosion processes, thus, further destructing the subsistence basis.

From this statement a number of conclusions can be drawn for the dynamical behavior of the variables LA, LW, and QR. First of all the ongoing erosion processes hint to a decreasing quality of the resource base and thus, using the notation introduced in section 3, we have QR $= \downarrow$. Second, the strong reliance on subsistence agriculture hints to a non-decreasing activity in agriculture. Together with further information from the case study concerning an actual *increase* in the need to use natural resources for livelihood, we conclude that LA $= \uparrow$ and LW $= \downarrow$. We also can state that it is the agricultural activity in the region which is damaging to the natural resources.

Similar kind of arguments can be performed for the other case studies to end up with a specification of the recent histories in the study regions according to table 3. For LA a further specification is provided concerning its actual *level* with respect to its possible damage for the natural resource.

Table 3

Recent history in the case study regions, expressed in terms of the generalized variables LA (activity in agriculture and collection), LW (wage labor) and QR (quality of the resource affected by LA). For Ban Taohai the information is not sufficient to uniquely specify QR (see [23] for details).

Study region	Variable LA	LW	QR
Nepal, Botswana	damaging, $\downarrow$	$\uparrow$	$\downarrow$
Dominican Republic, Miombo, Eastern Cape Province	damaging, $\uparrow$	$\downarrow$	$\downarrow$
Bela Vista (Brazil)	only, $\circ$	0	$\downarrow$
Dois Irmãos (Brazil)	preserving, $\downarrow$	$\uparrow$	$\uparrow$
Ban Kouay (Laos)	damaging, $\uparrow$	0	$\downarrow$
Ban Taohai (Laos)	$\uparrow$	0	$\circ$ or $\uparrow$

5.3. The cause–effect scheme of labor allocation

Figure 5 depicts the cause–effect scheme proposed to be valid for all the case studies considered. Note that there are some interrelations for the change of a state variable instead of the variable itself. For example, the relation between LA and QR as depicted in the graph actually states: as more activity is put into agriculture, as stronger is the *increase* in soil degradation (compare the quotation from the case study on the Eastern Cape Province given above). Conversely, however, for a very low level of agriculture, like it is described for some regions in Botswana, there is a recovery of the soils. Also the change of collection techniques portrayed for the charcoal producers in the Dominican Republic apparently does correspond to a soil preserving level of agricultural techniques. It is thus appropriate to introduce a landmark-value called "ms" (= maximal sustainable agriculture) for which the rate of soil degradation vanishes. Below

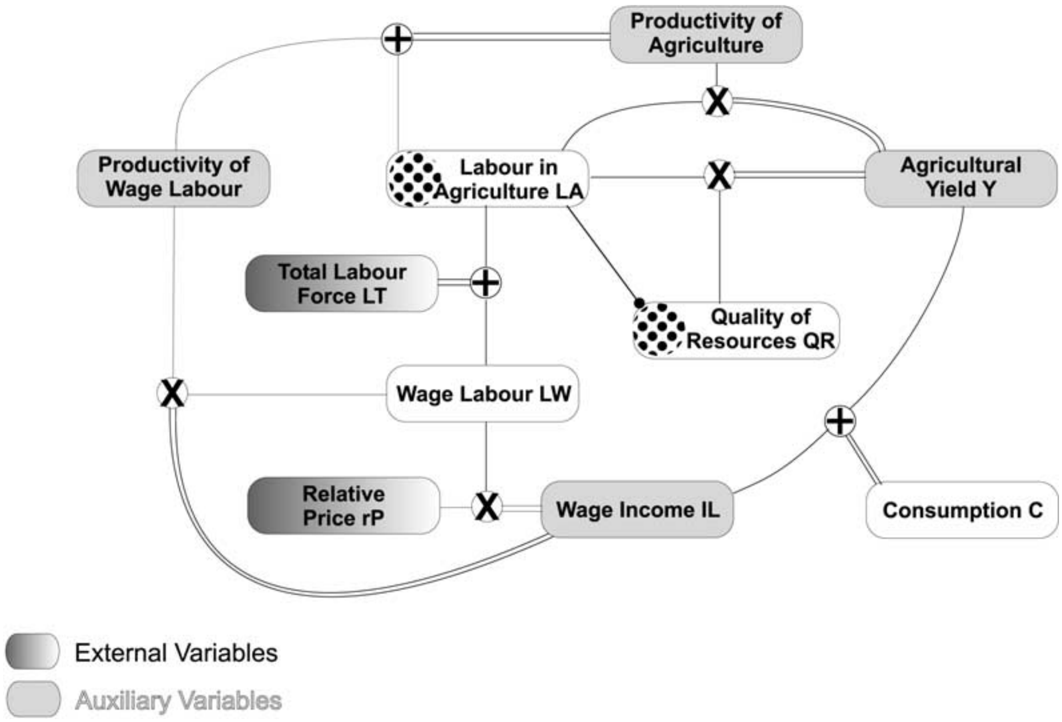

Figure 4. Qualitative model for integration of the case studies. The different lines and symbols encode actual realizations in the qualitative model, i.e., dotted areas: Temporal change of the variable; "+" qualitative addition; "x" qualitative multiplication; "—•" monotonously decreasing relation (see appendix).

that value a recovery of the natural resources is assumed to happen. Again it should be stressed that it is not necessary to attach any kind of number to this value. The knowledge of its existence is sufficient.

Other relations are actually based on general considerations, e.g., the qualitative multiplication for determining the yield from agricultural or collecting activities. It is obvious that the output Y depends on both, the quality of the resource (QR) and the investment of labor (LA). The specific form of this relation will vary largely over the different agricultural systems, including climate and soil conditions, techniques applied, etc. The properties which are common, however, are as follows. First, without any labor ($LA = 0$) or with vanishing quality ($QR = 0$; e.g., agriculture on rocks), no yield ($Y = 0$) will be achieved. Second, increasing QR or LA while keeping the other value constant will increase Y. Exactly these two (very weak) properties define the "qualitative product" in the QDE-formalism.

There is an important relation concerning the change of labor allocation built into the model. This rule is somehow hypothetical on the first view, as there is no clear indication for that to be found in the studies. It should be noted that without this allocation rule the model produces the same outcomes – but much more in addition to that. In particular many of the additional behaviors appear to be very unlikely. For example, if wage labor is hardly available and agriculture produces sufficient output then the model would still allow shifting the labor from agriculture to wage labor. The rule used to avoid these outcomes is as follows. The smallholder compares the recent outcome per labor unit of agricultural and wage labor. Labor is reallocated in the direction of the more labor efficient activity. This rule seems to be reasonable and it will turn out that it is in complete agreement with the observations. This hints to the fact that our integration technique also allows including further hypotheses not made explicit in the studies. The full model code is documented in appendix B.

5.4. The model behaviors

The model outcomes depend on the behaviors of some "exogeneously" determined variables, in particular the totally available labor LT, the relative price of agricultural produce, rP, and the availability of wage labor in the region. For sake of illustration we assume that the totally available labor force and the relative price remain constant. These are rather strong assumptions, as they exclude, e.g., the hypothesis that the need for additional work force in subsistence agriculture is one reason for population growth [37]. Yet, for the argument important here, i.e., that the histories of smallholder's agriculture as reported in the case studies are reconstructed, these assumptions are allowed, as the set of solutions obtained is a subset of the general set obtained without these assumptions.

The complete tree of behavior is depicted in figure 6. Concerning the general criteria of a limited number of behaviors we can conclude that the output of the model is rather convincing as a complete independence between the variables would produce some billions of behaviors, as can

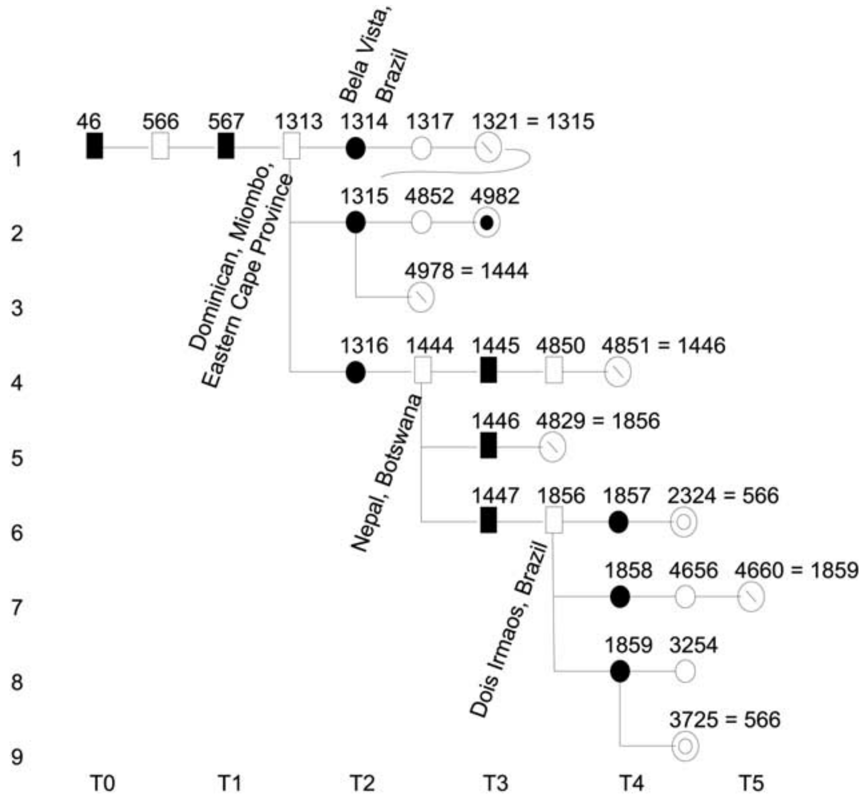

Figure 5. Behavior tree of the qualitative model for smallholder agriculture as specified in figure 4, representing the entire set of possible solutions. In addition to the symbols already introduced in section 3, the transition symbol ⦸ is used to indicate that the behavior continues at another node in the tree, given by the number on the right hand side of the identity indicated at the transition point. For example, the state S-1321 in the first behavior is identical to the state S-1315 in the second. Thus the first behavior is not truncated, but continues as the dashed line indicates it. The initial condition (S-46) is chosen such that – as is indicated by the labels bearing the names of the study regions and as discussed in more detail in section 5.5 – the recent history in all regions is part of the tree.

be computed by combinatorial methods based on the variable definitions.

One major function of this kind of model is its usage as a "thought-guide". In principle each behavior is also derivable by pure argument, which actually relates it to the field of "Artificial Intelligence". Yet one can never be sure to cover *all* possible behaviors, in particular those, which are surprising, unexpected and might bear heavy impacts in terms of sustainability. Yet starting inversely, i.e., with the behaviors obtained from the formal analysis one can develop the argument for *each* behavior.

In order to illustrate the usefulness of the model as a "thought-guide" we take a closer look at three of the behaviors (figure 7). It can be seen that in behavior 2, depicted in panel (a), the labor force is eventually completely allocated to agriculture and wage labor is no longer pursued. Correspondingly the quality of the resource is decreasing and in the end there is a complete loss of the natural grounds of agriculture (QR $= 0$). This solution can be viewed as non-sustainable and from the behavior it can be seen that the final outcome is already determined by the qualitative state in the time interval $(T2, T3)$ which *irreversible* ends with a vanishing quality of the natural resource.

In contrast, behavior 6 in panel (b) shows a cyclic behavior: in the beginning there is an increase in agriculture, which at time $T1$ reaches the non-sustainable level. Therefore the quality of the natural resource declines afterwards. Due to this decline of the quality, however, agriculture becomes less and less productive, till at time $T2$ wage becomes equally attractive. Correspondingly agriculture now is abandoned and wage labor is extended. This leads finally to a recovery of the natural environment (after time $T3$), which now increases the agricultural yield again. Due to this increase, the benefits of agriculture outpace those of wage labor at some later time $(T4)$. This again leads to an increase of agriculture for sake of reducing wage labor. The cycle is complete.

Finally, behavior 8 (c) exhibits a complete abandonment of agriculture in favor of wage labor (after $T4$). Correspondingly the natural environment is recovering. In contrast to behavior 2 this solution can be viewed as rather favorable as not only the environment is preserved, but the consumption, not shown in the panel, exhibits a satisfying level.

What are the decisive factors whether one or the other behavior is realized? In order to discuss this question, we recall that the single time-points in the behaviors are specified by *events* which are given by one or more variables reaching a landmark-value in their quantity space. First of all it can be seen that up to time interval $(T1, T2)$ the three solutions display the same behavior. Time $T2$, however, is de-

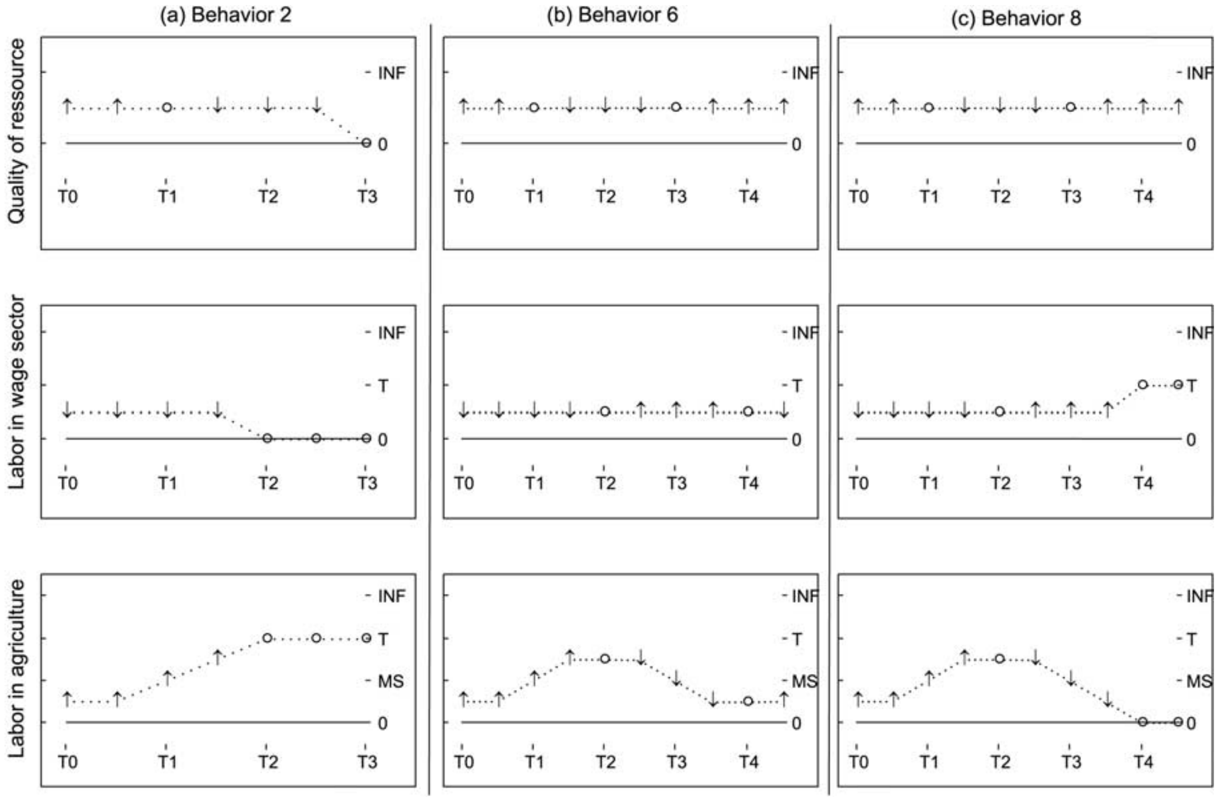

Figure 6. Qualitative time-plots for three out of nine behaviors. The behavior numbers on top refer to the behavior tree in figure 6. For a detailed discussion see text.

termined by different events for behavior 2 on the one hand and behaviors 6 and 8 on the other hand. In all cases labor allocation does not change anymore, i.e., LA and LW do not change as indicated by the circles in the respective plots, In the first case, however, this at a vanishing level of wage labor (LW $=$ 0) whereas for behaviors 6 and 8 some work force is still used in the wage labor sector. Thus one prerequisite to avoid behavior 2, characterized as unsustainable, is to provide enough well paid wage labor in order to pass up a complete allocation into agriculture.

The decisive event to discriminate between behaviors 6 and 8 occurs at time $T4$. Again no change in labor allocation happens at this time. Now, however, the question is whether labor is completely invested into wage labor or not. If so (behavior 8) there is a chance to achieve the solution which ensures a sustaining trend in improving the quality of resources QR. Otherwise the cycle of degradation and impoverishment starts over again which might again endanger the natural environment. Conclusively, we can state, that the *sufficient provision of wage labor to support the smallholders livelihood is a decisive factor for an environmentally and socially sound development.*

The limiting factor in a purely positive evaluation of this wage labor preference is, however, twofold: firstly, we have neglected any negative social or environmental impacts of wage labor and second, we have not evaluated the *cultural dimension* of the preference of the smallholders with respect to wage or agricultural labor.

5.5. Integration of case studies

In the previous section we have discussed some of the general features of the qualitative model. The model has been shown to produce "reasonable" results, but this is not sufficient to prove its applicability to the different case studies. In order to establish applicability we have to check whether the recent histories in the regions as specified in terms of the main qualitative variables (table 3) can be found in the set of possible solutions.

The result of this check is depicted by the labels in figure 6 carrying the names of the study regions. For five of the regions (Dominican Republic, Miombo Highlands, Eastern Cape Province, Nepal, and Botswana) a unique qualitative state can be identified. According to the necessary differentiation within the study region in the Atlantic Rainforest in Brazil, two different states are recognized in the behavior tree. The case study of Laos cannot be integrated into the behavior tree in figure 6. This is due to the non-availability of wage labor in the region, i.e., the allocation rule implemented in the model is not applicable. It turns out, however, that the recent situations in Laos can be reconstructed if we modify the model by preventing any labor allocation into the wage labor sector (for details see [23]).

It can be stated that the integration of the case studies into the behavior is successful. We therefore can use the model to shed some lights on the near term prospects in the single study regions.

Table 4
Short term prospects for the different study regions as suggested by the qualitative model. The results for Laos are obtained by enforced avoidance of wage labor and can therefore not be identified with states in the behavior tree in figure 6. The perspectives arising from these "restricting" prospects is in more detail discussed in the text.

Study region	Next possible qualitative state			
	LA	LW	QR	No. in tree
Nepal, Botswana	>ms, ↓	↑	0	1445
	ms, ↓	↑	0	1446
	ms, ↓	↑	°	1447
Dominican, Miombo, E. Cape Province	T, °	0	↓	1314/5
	>ms, °	< T, °	↓	1316
Bela Vista, Brazil	>ms, ↓	↑	↓	1444
	T, °	0	↓	4852
Dois Irmãos, Brazil	< ms, °	< T, °	↑	1857
	0, °	T, °	↑	1858/9
Ban Kouay, Laos	>ms, ↑	0	↓	–
Ban Taohai, Laos (for the two different	ms, ↑	0	°	–
options given in table 3)	>ms, ↑	0	↓	–

- *Nepal and Rural Botswana*: Though for different reasons and by different political measures, in both regions a recent increase in wage labor can be observed. Whereas in Nepal this is due to the willingness of the local people to commute large distances, in Botswana a remarkable drought relief program had been installed by the government. The near future is strongly dependent whether the abandonment of agriculture in marginal areas happens fast enough in order to prevent a further massive degradation of the natural environment. Political measures should therefore seek to strengthen the provision of wage labor and to avoid any incentives for agriculture.
- *Dominican Republic, Miombo Highlands and Eastern Cape Province*: In these regions agriculture is still the major source of income and strongly related to a growing soil degradation. The perspectives of alternative sources for livelihood are not sufficient and there is thus a danger for irreversible damages to the environment. In order to avoid this kind of a development it is highly necessary to provide off-farm options for income. At this point a short excursion concerning the usability of qualitative modeling for policy evaluation is in place. In the study in the Dominican Republic the German Society for Technological Cooperation (GTZ) has installed a project called Proyecto Bosque Seco. The project intents to introduce more sustainable methods of forest management for the charcoal burners, e.g., by motivating the use of dead instead of living wood. It also includes measures to reduce the time burden of transporting the charcoal to the nearest town which is some 10–15 km away. It is obvious that our model cannot endogenize this measure directly, yet it has been shown that these kinds of exogeneous policy measures can be included into the qualitative modeling exercise as a "jump" within the behavior tree [20]. To illustrate that, consider the measures taken by the GTZ-project. Introducing new, resource preserving management methods and keeping everything else constant, results in the effect, that the same amount of labor allocated to wood collection and processing which has had a damaging effect on the environment before, is now actually environment preserving. Put into the terms of qualitative modeling this implies, that after the installation of the program the value of LA is *below* its maximal sustainable level ms, whereas it had been above this value before the installation. This, however, is another qualitative state. In case of the project in the Dominican Republic, for example, the state before the measure was taken is numbered as 1313 in the behavior, whereas the state afterwards is 566. This implies, however, that if no further actions are taken the situation might not improve significantly as according to the model the state of affairs in the region eventually will resume its original state (note that there is no bifurcation between states 566 and 1313). This corresponds to the fact that due to attractiveness of the program more and more charcoal burners like to join which finally again induces an unbearable pressure on the environment.
- *Atlantic Rainforest, Brazil*: For Dois Irmaos there is a option for a good future as long as wage labor keeps to be attractive enough to avoid the shift back to agricultural activities. For Bela Vista, however, there is a high danger for a complete overuse of rainforest. If it is not possible to provide wage labor for the smallholders in the village the rainforest in the area might finally disappear. This decisive element is described by the bifurcation at state 1315 in the tree where either behavior 2 (see panel (a) in figure 7), which had been identified as non-sustainable, is followed, or agriculture is started to be abandoned which would open some perspective.
- *Laos*: As mentioned before the situation in the study region is characterized by a complete absence of wage labor and can thus not be covered by the general model. The possible successors as indicated in table 4 have been obtained by a model which has been appropriately modified. As for the study on the Atlantic Rainforest in Brazil two different situations are present. For Ban Taohai the recent situation exhibits some positive signs as the agricultural activities do not put too much pressure on the environment. Yet these positive signs are somewhat endangered as a further intensification might significantly increase the pressure (decreasing or at most steady quality of the resource QR). In contrast the agricultural activities in Ban Kouay already put a significant pressure on the natural resources and if no external support is provided a further loss and even a complete diminishing of the natural basis for agriculture might dawn.

Together with an assessment on the sensitivity of the agricultural productivity against climate change [38] these results have been used to obtain a ranking of the study regions in terms of near term criticality [23]. Within this ranking the absence of wage labor and the high sensitivity against climate have put Laos on the first place, whereas the situation in the Atlantic Rainforest in Brazil seems to be ranked last. This is due, among others, to the fact that agricultural marginality in this region is mainly due to restrictions in soil fertility and climate change is thus of minor importance for the prospects of agricultural productivity.

6. Conclusive remarks

In this paper we have demonstrated how a qualitative modeling approach can be used to integrate and compare regional case studies on Global Change issues. This approach stands in between an "atomistic" concept and a mono-causal approach. Whereas in the first a detailed modeling of each region would be needed, the latter would head for a single, quantitative model for all regions characterized by simple statements like the well-known IPAT-Formula (Impact = Population × Affluence × Technology). Both extremes are avoided by our approach as it makes use of the well-defined generalizing features of qualitative differential equations as the basic modeling tool. The following conclusion can be drawn on basis of the hypotheses formulated in section 2.

1. The qualitative modeling method had been shown to be useful to formulate and validate a set of relationships capable to describe land-use changes by smallholder agriculture in different regions of the world. Due to the well-defined generalization scheme of the underlying concept of qualitative differential equations the methodology largely avoids a subjective generalization based on individual views, experience and knowledge.
   It is rather obvious that the model presented here will not be capable to describe land-use changes in the developed world, thus another set of qualitative relationships is needed to do so. On the other hand, it should be expected that the model can well cover other histories of smallholders agriculture in marginal areas in the developing world. We, therefore, can state that this specific set of relations constitutes a *pattern of civilization-nature interaction* as will the other qualitative models do for other situations. The scheme does aggregate some but avoids to treat all situations alike. This is actually what patterns are supposed to do.
   In principle, however, there is a second level of pattern formation *within* a single cause–effect-scheme. As the model produces not a single solution, but a set of possible behaviors compatible with the cause–effect-scheme, it might well be the case that different parts of this behavior tree are well separated from each other. In this case the two parts of the tree represent two general classes of behaviors, which might be considered as 2nd order patterns. This situation, however, does not occur within the model presented here, but can well be found in other applications.
   It has to be stressed that it is necessary to couple the different qualitative models in order to get an overall picture of Global Change. The idea is, however, that the couplings are much weaker than the internal interactions of a model and that therefore the single model largely determines the dynamical behavior. Yet a profound methodology for model coupling is still missing. Here some more research is needed.

2. The qualitative modeling approach has been shown to be useful to obtain basic features of a complex interplay between natural and socio-economic aspects of Global Change issues. The modeling scheme does not make use of quantitative relationships based on statistical grounds, e.g., using a necessary parameterization scheme. Instead it applies purely symbolic manipulations to obtain these features. It could be shown, for example, that the sufficient provision of income opportunities in wage labor activities plays a key role to avoid the overuse of marginal lands. Due to the interplay between income activities and environmental degradation we have shown that cyclic behaviors are possible where the temporary abandonment of agriculture in favor of wage labor can contribute to recovery of the natural resources. Finally these resources might be used again. This is a different version of the well-known shifting cultivation procedure.
   These features can of course also be obtained from conventional, quantitative modeling. But in order to do so much more information is needed to specify the quantitative relations – information which is often vague or uncertain. The qualitative modeling approach claims to cope better with this kind of knowledge. Yet care has to be taken, as even the qualitative relationships can be uncertain.

3. We have demonstrated how qualitative information from different case studies on similar issues of Global Change can be used as an information base for the modeling exercise. This applies for the formulation of the model (see [23] for more details) as well as for the validation – or better: non-falsification – of the model. By representing the history as described in the case studies, it can be checked whether the same qualitative model reconstructs these historical observations. It should be stressed that "reconstruction" here means the complete coincidence between model behaviors – or temporal sections of it – and the qualitatively specified regional histories.
   Furthermore we have illustrated how the qualitative model can be used as a "thought-guide" for arguing about mechanisms and possible futures. This makes clear, that the model itself does not act as a black box and that its outcomes are still subject of debate. Thus this approach must not be seen as merely focused on "blind" projection, but on system analysis also. It should help to identify the most important mechanisms, and in its role as "thought-guide" its ability to surprise, i.e., to help thinking about mechanisms and their interactions not thought before.

4. The set of possible behaviors obtained by our model gives also some insight into the question of dynamically specified paths of non-sustainability. One of the behaviors (behavior 8, figure 6(c)) depicts the possibility of an ever-

growing degradation of the natural resource. This behavior occurs, if the wage labor is insufficient to represent an alternative way of income and thus enable the smallholder to give up agriculture. Agriculture is continuously expanded to ensure the livelihood. This corresponds to the classical impoverishment-degradation spiral [34] and there is no way out of this as long as no alternatives are provided.

It should be stressed that the model presented here constitutes only a first step to a more general description of smallholders' agriculture in developing countries. There are many case studies which cannot be integrated into it. Yet it was not the purpose to present a completed model, but to illustrate the features, strengths and also deficiencies of the qualitative modeling approach and to motivate its usage in other fields of Global Change Research.

Acknowledgements

We would like to thank the whole QUESTIONS group at PIK for supporting this paper, in particular Oliver Moldenhauer for his contributions to the qualitative models, Fritz Reusswig and Martin Cassel-Gintz for fruitful discussions on many "semantic" aspects and Hans-Joachim Schellnhuber for stimulating and promoting this new branch of research.

Furthermore we like to thank Jan Rotmans, Jeanne and Roger Kasperson, and Heidrun Mühle for inspiring discussions on the ideas of the approach.

Appendix A. Logistic growth with constant withdrawal

lisp – model code defining the problem for QSIM	For comprehensive explanations see [16] def.: $[x]_a = \mathrm{sign}(x - a)$
`(define-QDE lgcw`	
`(text "Simple Ecosystem with constant Yield")`	
`(quantity-spaces`	*Definition of variables and their landmark-values*
`(P     (0 Po Pm out) "Population")`	
`(dP (minf 0 inf) "Change in Population")`	minf $= -\infty$; inf $= +\infty$
`(G (minf 0 Go inf) "Growth without Yield")`	
`(E (0 inf) "Yield"))`	
`(constraints`	*Definition of interrelations*
`((d/dt P dP))`	$[\mathrm{d}/\mathrm{d}t\,P]_0 = [dP]_0$
`((U- P G (Po Go)) (0 0) (Pm 0) (out minf))`	see text
`((CONSTANT E))`	$[\mathrm{d}/\mathrm{d}t\,E]_0 = 0$
`((add dP E G)))`	$[\mathrm{d}P]_0 + [E]_0 = [G]_0$, same for derivatives $[-]_0 + [+]_0$ and $[+]_0 + [-]_0$ undetermined
`(defun anf ()`	
`(make-new-state :from-qde lgcw`	*Definition of initial state*
`:assert-values '((P (Pm nil))`	$P = P_m$, direction of change undetermined
`(E ((0 inf) std)))`	E positive definit and constant
`:text "1"))`	
`(defun start_env ()`	*Producing the behaviour-tree for the above initial state*
`(with-envisioning`	
`(let ((initial-state (anf )))`	
`(envision-guide initial-state))))`	

Appendix B. Smallholder model for ressource degradation and labor allocation

lisp – model code defining the problem for QSIM	For comprehensive explanations see [16] def.: $[x]_a = \mathrm{sign}(x - a)$
`(define-QDE smrdla`	
`(text "Shmallholder with LA-LW-allocation")`	
`(quantity-spaces`	*Definition of variables and their landmark-values*
`(LT (0 t inf)            "Total labor")`	

```
  (LW    (0 t inf)    "Labor in wage sector")
  (LA    (0 ms t inf) "Labor in agriculture")
  (QR    (0   inf)    "Quality of  resource")
  (Y     (0 inf)                     "Yield")
  (rP    (0 inf)        "relative Price A/W")
  (dLA   (minf 0 inf)         "Change of LA")
  (dQR   (minf 0 inf)         "Change of QR")
  (CT    (0 inf)         "Total consumption")
  (CL    (0 inf)              "Labor income")
  (f0    (minf 0 c inf)               "aux0")
  (f1    (minf 0 inf)                 "aux1")
  (f2    (minf 0 inf)                 "aux2"))
```

see appendix A

```
 (constraints
  ((d/dt QR dQR))
  ((d/dt LA dLA))
  ((add LA LW LT) (0 t t) (t 0 t) )
```

Definition of interrelations
see appendix A
"
additionally to appendix A:
$[\mathrm{LA}]_0 + [\mathrm{LW}]_\mathrm{t} = [\mathrm{LT}]_\mathrm{t}$ and
$[\mathrm{LA}]_\mathrm{t} + [\mathrm{LW}]_0 = [\mathrm{LT}]_\mathrm{t}$

```
 ;dynamics of QR
  ((M- LA f0) (0 c) (ms 0) (inf minf))
```

$[\mathrm{d}/\mathrm{d}t\mathrm{LA}]_0 = -[\mathrm{d}/\mathrm{d}t f0]_0$;
$[\mathrm{LA}]_0 = -[f0]_\mathrm{c}$; $[\mathrm{LA}]_\mathrm{ms} = -[f0]_0$
$[\mathrm{LA}]_\mathrm{inf} = -[f0]_\mathrm{minf}$

```
 ((mult f0 QR dQR))
```

$[f0]_0 * [\mathrm{QR}]_0 = [\mathrm{dQR}]_0$

```
 ; yield and consumption
  ((mult LA QR Y))
  ((mult LW rP CL))
  ((add Y CL CT))
 ;allocation of labor
  ((add f1 rP QR))
  ((mult LA LW f2))
  ((mult f1 f2 dLA))
  ((constant LT))
  ((constant rP))
 ))
```

see above
"
"
"
"
"
"
"
"

```
(defun anf ()
    (make-new-state :from-qde smrdla
         :assert-values '((LT (t  std)
                         (LA ((0 ms) inc))
                         (LW ((0 t) dec))
                         (QR ((0 inf) inc))
                         (rP ((0 inf) std)))
                 :text "2"))
```

Definition of initial state
$\mathrm{LT} = t$ and constant
$0 < \mathrm{LA} < \mathrm{ms}$ and increasing
$0 < \mathrm{LW} < t$ and decreasing
QR pos. def. and increasing
rP pos. def. and constant

```
(defun smrdla _env ()
  (with-envisioning
      (let ((initial-state
          (anf )))
    (envision-guide initial-state))))
```

Producing the behaviour-tree for the above initial state

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