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The Syndromes Approach to Scaling

Describing Global Change on an Intermediate Functional Scale

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ABSTRACT

A dynamic description of Global Change on an intermediate functional scale on the basis of approximately independent sub-models is elaborated. Sixteen of these sub-models are primarily identified as *Hazardous Functional Patterns* (HFPs) generating non-sustainable trajectories (*Syndromes*) of the civilisation/nature system. After an ''idealistic deduction'' of the main concepts an iterative procedure – formally based on Qualitative Differential Equations – is introduced which allows the systematic generalisation of case study based knowledge to obtain consistent HFPs on a coarser functional scale. The method is illustrated with the Sahel HFP.

Keywords: intermediate functional scale, qualitative modelling, Syndrome, Global Change.

1. DEALING WITH GLOBAL CHANGE – THE SCALING PROBLEM AS ONE CRUCIAL ASPECT OF COMPLEXITY AND UNCERTAINTY

Today, it seems obvious that Global Change (GC) research has to take care of the high level of complexity present in the interactions between civilisation and nature. Complexity – synonymous for the multitude and non-linearity of the interrelations between and within all the various facets of global environmental change and its socio-economic drivers and impacts on their respective spatial, temporal and functional scales – brings about a number of generic difficulties:

- There is no such thing as ''prediction'' in a strong sense, i.e., even in principle it is not possible to give exact statements like ''in 2010 the global – or national – CO_2 emissions will be 42.3 Gt.'' Usually, those modellers of Global Change who actually give these kinds of statements qualify those by adding: ''Don't trust the numbers, just trust the trends.'' But why should we do that? Models per se – though probably the only way to reflect the world's complexity at all – do not guarantee the correct reflection of complexity.
- One important fact generating uncertainty is the scaling problem. The scientific knowledge about relevant processes of GC is usually on the level of their ''natural scale'' (defined by the scale of observation or the scale of the underlying ''first principles''). Now the interactions of processes across different scales require up- or downscaling procedures which mostly transcend the scope of the original scientific knowledge about these processes (see, e.g., the examples in Root and Schneider [1]).
- Any kind of political strategy against some non-sustainable development within global change brings about the risk of triggering a vast variety of extra effects, either wanted or unwanted. This situation is comparable with a patient attending a doctor. Prescribing a medication against one symptom might well induce another symptom, which itself has to be treated using another treatment. This cycle repeats itself, unless one is able to identify the underlying disease – or Syndrome – in its totality and to prescribe a general therapy against the disease itself.

These considerations illustrate that it is necessary to take into account Earth System complexity in an appropriate manner when dealing with GC [2, 3].

There are further aspects of Global Change which enhance the difficulties of modelling and analysing the current path of apparent non-sustainability. There is not only the ''complexity-induced uncertainty'' discussed above, but also the ''modular'' or ''holistic/reductionistic uncertainty'' about single issues and relations being part of the highly interconnected global network of interrelations. Knowledge of many relations constituting the overall complexity is vague, incomplete or only qualitatively available. It is not

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necessarily the case that these uncertainties can be resolved over time: social, cultural or political issues are qualitative in nature and one cannot expect that there will be, e.g., a quantification of the old Weberian relation between Protestantism and the ethics of capitalistic activity [4] – let alone that there will be a "proof" in the sense of mathematics or physics.

At this point one might argue that complexity and non-quantifiability constitute natural constraints for any kind of modelling or formal analysis. The dilemma is that the mathematics and physics of complex systems tell us that we actually need some kind of formal analysis: due to the non-linearities in the system, counter-intuitive surprises can happen which can only be detected or anticipated by the use of advanced calculus. But it is not only this experience which tells us about the need for a formal, preferably model-based approach; it is also the dilemma between relevance and the importance of waiting for empirical evidence: anthropogenic climate change never would have been a subject for the public without any modelling exercises!

Some people therefore start "to quantify the non-quantifiable," sometimes by methods like willingness-to-pay, i.e., approaches which are intrinsically consistent, but which ethically remain doubtful (e.g., when monetising human life). From our point of view this approach remains questionable as it neglects the advantages of qualitative research.

To sum up, we state that the complexity of the Earth System requires a modelling approach [5] which is capable of incorporating this complexity in an appropriate manner by allowing to integrate incomplete, vague or qualitative knowledge into its formal framework. In this paper we will elaborate on the Syndromes approach which is an attempt to meet these aims.

2. IDEALISTIC DEDUCTION VERSUS REALISTIC INDUCTION

To explain the general systems-theoretical idea behind the Syndrome concept we will start with a (necessarily) hypothetical situation which would allow Syndrome identification in a deductive way. Let us assume a system of ordinary differential equations (ODE) which represents the whole global dynamical system, including all relevant aspects of the natural, social, economic and cultural spheres and their complex interactions. Here the spatial aspects are included by discretisation which means that the interaction between different scales is formulated explicitly. Insofar this hypothetic system of ODEs includes the correct methods of upscaling (e.g., as a simple case the summing up of CO_2 fluxes from all the heterogeneous sources) and downscaling (e.g., the regionalisation of climate change to calculate its feedback on carbon sources). For a more complete review of scaling issues in the anthropospheric part of the Earth System see, e.g., Gibson et al. [6], while for the natural science side Root and Schneider [1] give further examples.

Using any set of variables we would now expect a very large number of these variables and most of the equations of this system to be closely interlinked, leaving us with an intractable problem. One option to tackle such a complex system is to decompose its dynamics into several components that are approximately independent. One way to achieve this is to transform the variables of the system in such a way that the system decomposes into several, only weakly interacting sub-systems. As an example from physics consider the well-known two body problem which separates completely in one sub-model for the relative motion of the masses and one sub-model for the dynamics of the centre of mass. By introducing a small third mass the two sub-systems become weakly coupled [7]. In general, decoupling can be achieved by a canonical transformation. The resulting sub-models are denoted in our terminology as functional cause-effect patterns. However, since we are mainly interested in non-sustainable behaviours, we concentrate in the Syndrome concept on those functional patterns that exhibit at least one non-sustainable trajectory, the so-called Syndrome-prone or *Hazardous Functional Patterns* (HFPs). The class of non-sustainable trajectories resulting from one of these functional cause-effect-patterns is called "*Syndrome*" and we will see that it represents a sub- or *Detailed Functional Pattern* (DFP).

As described above, these patterns are constructed so that their solutions decouple as much as possible. This is generally not feasible, so that there remains some degree of inter-pattern interaction which will be often found on the macro-scale (e.g., macro-economical relations, climate change caused by greenhouse gas emissions etc). In the above (hypothetical) formulation of the Global System spatial interactions (and therefore also spatial interactions across different scales) are not distinguished from other, more functional forms of relations. This illustrates the equivalence of scaling and functional aspects in formulating the sub-systems according to the given criteria.

The basic variables for the formulation of the functional patterns are called, again in analogy to medicine, the "*Symptoms of Global Change*" [8]. Their number should be much lower than the number of variables one expects for the hypothetical complete world model, so one important way to go from the hypothetical fundamental variables to the *Symptoms* is by aggregation, which has to be done in a way that the interactions of the aggregate *Symptoms* are (almost) sound aggregates of the underlying basic interactions. This aggregation rule, leading to a more coarse functional resolution in accordance with lower scale processes can be denoted as "*functional scaling up*." Another criterion refers to time scale: variables which are slow compared to relevant time scales of GC (the latter being decades to centuries) can be interpreted approximately as constant boundary conditions and can be therefore omitted as dynamic variables or *Symptoms*, while very fast processes can be described by their equilibrium states as determined by the variables of the

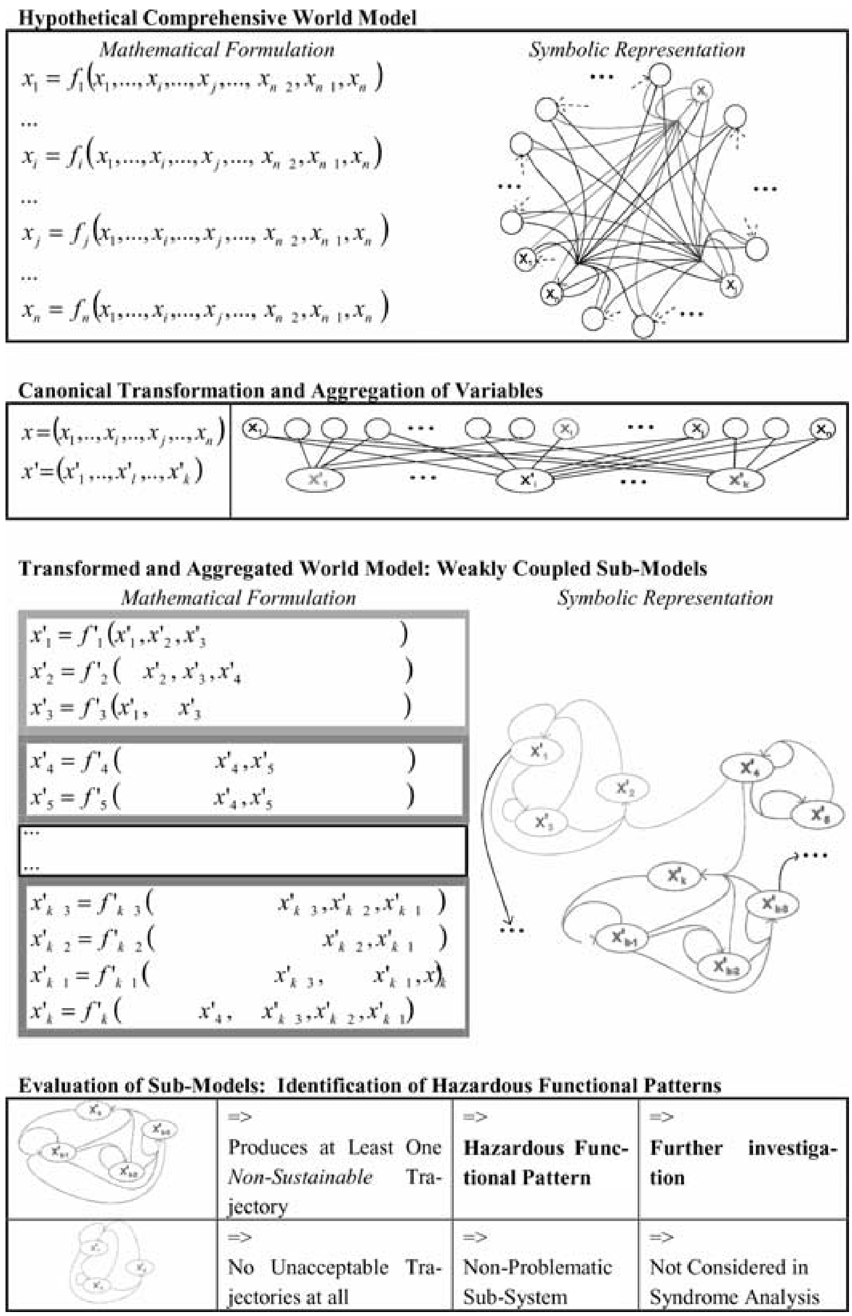

Fig. 1. Hypothesized process of the deduction of *Hazardous Functional Patterns* producing *Syndromes* as classes of non-sustainable time behaviours.

relevant time scale which reduces the number of dynamic relations (“adiabatic technique,” see, e.g., Haken [9]). As mentioned above, a further important criterion for the selection of *Symptoms* is the goal of having not too many or too strong interlinkages between the *Symptoms* involved in one *Hazardous Functional Pattern* to those of another pattern. Most *Symptoms* are spatially resolved with a “natural” spatial scale as determined by the patterns of interactions they are involved in, which also makes *Hazardous Functional Patterns* and *Syndromes* local or regional entities. The whole process is summarised in Figure 1.

There are several well-accepted reasons why the starting point for the above argumentation, the system of ODEs which represents the entire global dynamical system, is necessarily hypothetical: our knowledge of the relevant functional relationships is:

- uncertain,
- incomplete, including the lack of up- and down-scaling rules,
- partly of irreducible qualitative nature,
- partly controversial.

Therefore, the strictly deductive way of identifying *Hazardous Functional Patterns* (HFPs) and their *Syndromes* is intractable, but illustrates the general idea and the concepts which can be maintained in a more inductive process. Syndrome identification has to start from:

- the limited but presently available knowledge of quantitative or qualitative functional relationships with respect to Global Change,
- the conditions of the validity of these interactions,
- the knowledge of problematic environmental and socio-economic developments.

This knowledge is exemplified by the Bretherton diagram for the natural science part of Global Change research [10] and a diagram for socio-economic drivers and consequences of land use changes on top of Figure 2 [11]. Beside this (often large-scale) functional knowledge, detailed, small-scale knowledge from case studies (e.g., Kasperson et al. [12]) is available (bottom of Fig. 2). The functional resolution of HFPs and therefore of the *Syndromes* (center of Fig. 2) lies in between these two extreme scales (''*intermediate functional scale*''). Thus one avoids to get lost in the details of an immense amount of different case studies and, on the other hand, to be too general to meet the necessary minimal differentiation (e.g., for at least weak forms of prognosis), especially at the civilisation – nature interface. While we describe in the remaining part of this section a more inductive approach to tackle this problem, a more formal iterative method based on qualitative differential equations is introduced in the next section (see also Petschel-Held and Lüdeke [13]).

Given the information base on functional knowledge, the first step is to define variables describing Global Change (''*Symptoms*'') according to the criteria defined above in the hypothetical deduction of the Syndrome concept from a complete Earth System model: they must help to decompose the complex global system in almost independent subsystems while the important interactions between the original variables must remain discernible. This implies choices about aggregation and ''*functional resolution*.'' A first list of about 80 of these variables or ''*Symptoms*'' was suggested by the WBGU [14] and developed further by the QUESTIONS project [15].

Then, the second step is to group the huge number of interactions between the *Symptoms* in functional patterns producing syndromatic behaviours (and possibly others).

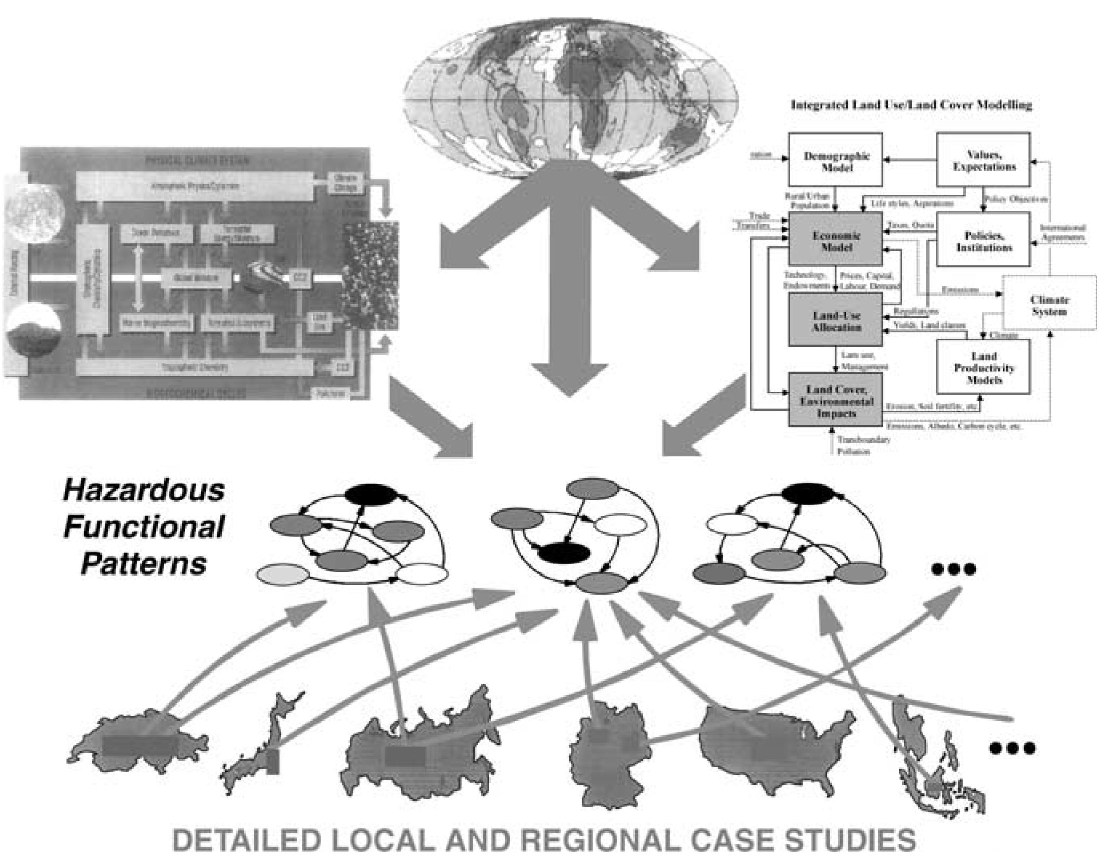

Fig. 2. Approaches for identifying of *Hazardous Functional Patterns* (''**intermediate functional scale**''): general functional knowledge and problematic global developments (top-down) versus generalisation of detailed case studies (bottom-up).

Table 1. Syndromes of global change.

a) Utilisation *Syndromes*
Sahel Syndrome: *Overcultivation of marginal land*
Overexploitation Syndrome: *Overexploitation of natural ecosystems*
Rural Exodus Syndrome: *Environmental degradation through abandonment of traditional agricultural practices*
Dust Bowl Syndrome: *Non-sustainable agro-industrial use of soils and bodies of water*
Katanga Syndrome: *Environmental degradation through depletion of non-renewable resources*
Mass Tourism Syndrome: *Development and destruction of nature for recreational ends*
Scorched Earth Syndrome: *Environmental destruction through war and military action*
b) Development *Syndromes*
Aral Sea Syndrome: *Environmental damage of natural landscapes as a result of large-scale projects*
Green Revolution Syndrome: *Environmental degradation through the introduction of inappropriate farming methods*
Asian Tigers Syndrome: *Disregard for environmental standards in the course of rapid economic growth*
Favela Syndrome: *Environmental degradation through uncontrolled urban growth*
Urban Sprawl Syndrome: *Destruction of landscapes through planned expansion of urban infrastructures*
Disaster Syndrome: *Singular anthropogenic environmental disasters with long-term impacts*
c) Sink *Syndromes*
Smokestack Syndrome: *Environmental degradation through large-scale diffusion of long-lived substances*
Waste Dumping Syndrome: *Environmental degradation through controlled and uncontrolled disposal of waste*
Contaminated Land Syndrome: *Local contamination of environmental assets at industrial locations*

Here the spatial and functional conditions of the validity of interactions play an important role: a necessary condition that two particular interactions which have one *Symptom* in common (e.g., *globalisation of markets* causing *agricultural intensification* and *agricultural intensification* leading to *loss of biodiversity*) belong to one submodel is spatial coincidence. But this is not sufficient because further functional conditions may assign the interactions/symptoms to, e.g., different economic sectors or groups of actors, which may coexist at one location assuming a realistic spatial resolution (e.g., *poverty* of different social groups in a city will have different effects on, e.g., *migration*).

A list of 16 *Syndromes* is given in Table 1 which was suggested by the WBGU [14] and developed further by the QUESTIONS [15] project. The short descriptions given in the table reflect important aspects of the respective *Hazardous Functional Pattern* (HFP). Due to the limited knowledge base used for the identification of the functional patterns and the *Syndromes* they must be interpreted as educated first guesses which have to be corroborated in the usual process of verification/falsification/modification. Because *Hazardous Functional Patterns* are very abstract and deep causal concepts, they cannot be checked directly. Instead of this, results deduced from them have to be compared with observed phenomena. Figure 3 gives one example for a *Hazardous Functional Pattern*. This pattern generates as one class of its possible behaviours the Sahel Syndrome [15].

One first step of validation is the data-based Syndrome diagnosis. Here we calculate from the structure of any *Hazardous Functional Pattern* the so called *Disposition* towards the *Syndrome*, which means that the most important mechanisms and interactions potentially may become active in a specific region. One important aspect in the definition of this concept is time-scale. Disposition usually depends on natural and socio-economic characteristics which are assumed to change slowly in time compared with the typical time scales of the *Syndrome*. In general, it will be necessary to describe the complex conditions for the potential validity of the main interactions by a relatively large set of hierarchically ordered indicators, which can be illustrated by a decision tree, showing the different hierarchical levels together with the logical relations between the basic indicators. An appropriate way to formalise this decision tree has to reflect the mostly qualitative nature of the Syndrome mechanism's description which implies the use of qualitative knowledge in the identification of Syndrome prone regions. Up to now the Fuzzy Logic concept [16] appeared to be most fruitful in this context [17].

As an example, the disposition towards the Sahel Syndrome will be discussed here. In this case one has to identify conditions for the following central interactions: (a) poverty-driven low capital intensification and expansion of agriculture causes soil degradation and (b) yield decline forces the poor rural population to further land use changes due to the absence of economic alternatives. In the case of this *Syndrome* the most important interactions (the "*Syndrome kernel*") operate on the same spatial scale, so there is no up- or downscaling problem included. Later we will discuss a extension of the model which allows to study the spatial interaction of dynamical structures resulting from the respective *Hazardous Functional Pattern*. Interaction (a) becomes probable if the considered region is fragile with respect to its natural conditions for agriculture ("natural

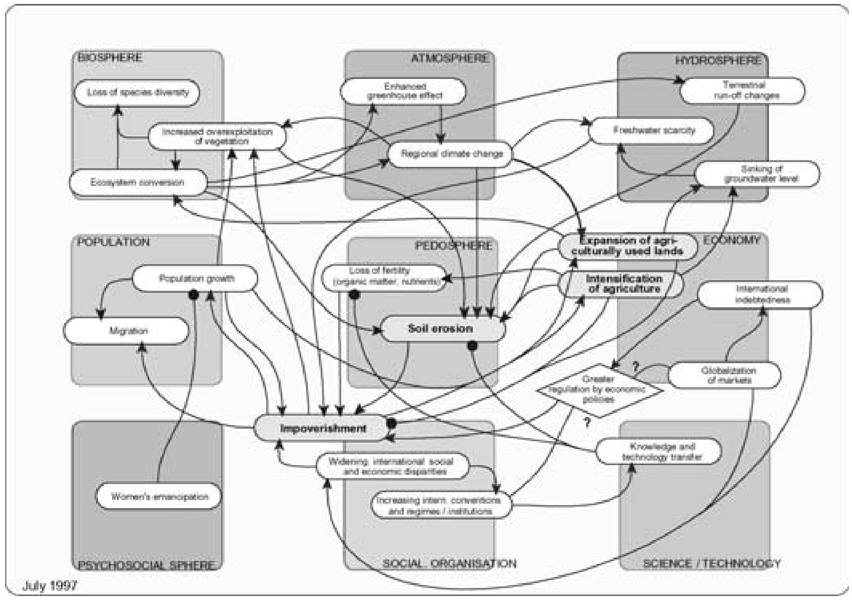

Fig. 3. Network of interrelations for the Sahel-Syndrome-generating functional pattern (Sahel HFP).

dimension''), while interaction (b) becomes probable if there is a high proportion of subsistence farming in a primary sector oriented economy (''socio-economic dimension''). Here it is assumed that the temporal change in the natural as well as in the socio-economic dimension is slow compared with the time scale of the degradation-impoverishment-spiral. This seems generally valid for the natural component (orography, climate, natural soil fertility, etc), while for the socio-economic conditions (e.g., sectoral structure of the economy) change could in principle occur on time scales comparable with the time scale of the Sahel-HFP dynamics – but the situation in almost all developing countries shows a

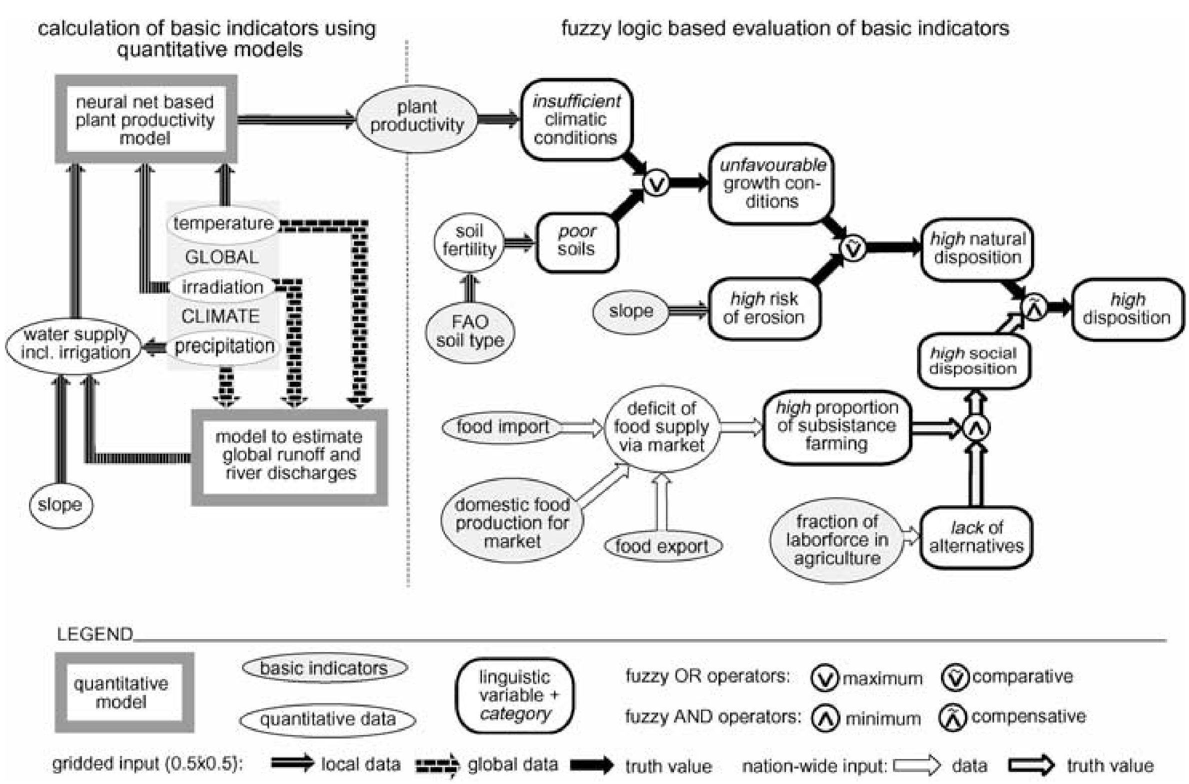

Fig. 4. Structure of the algorithm for calculating the disposition towards the Sahel Syndrome using elements of qualitative and quantitative modelling.

remarkable constancy in the dependence on smallholder agriculture including subsistence farming for significant parts of the population. Therefore the combination of a fragile resource basis and the lack of alternatives for livelihood is the fatal background for this syndrome dynamics.

In Figure 4 it is shown how these conditions are estimated on the basis of available global data sets and models. The latter include, e.g., for the natural dimension the net primary productivity of natural vegetation (NPP) as a basic input for general growth conditions (here as a modelled value considering the present climate) and the orography as an indicator for erosion risk. For the socio-economic dimension, data on the importance of the primary sector and market statistics for food products were used [18]. In the sense of a Fuzzy-Logic formalisation all linguistic categories indicated by rectangles in Figure 4 are characterised by membership indices between 0 (the category does not apply to the region at all) and 1 (the category applies definitely to the region). Accordingly, the circles depict appropriate fuzzy connections.

The global result (half-degree spatial resolution) of the algorithm is shown in Figure 5, presented as the membership-index with respect to high SAHEL-SYNDROME Disposition. It can be seen that even very fragile regions in industrialised countries (e.g., the Western USA) are not prone to the *Syndrome* because of the missing socio-economic conditions, while, e.g., in the Sahel region, in other parts of West Africa, the North East of Brazil, the West coast of South America, Mongolia and the West of the Indian sub-continent, both the social and the natural dimension apply, which results in a high disposition. In those regions the *Hazardous Functional Pattern* could be active, so those regions are either endangered by the outbreak of the *Syndrome* or the *Syndrome* is already realized.

Just to give an example on how these results of Syndrome diagnosis can be used in "classical" climate impact research, we show here the result of a sensitivity study with respect to climate change [18]. In Figure 6 this sensitivity, calculated as the absolute value of the gradient of the SAHEL SYNDROME *Disposition* with respect to climate, is presented. One can identify which regions are endangered to become disposed towards the SAHEL SYNDROME under climate change. This calculation becomes possible because agricultural plant productivity, one important indicator contributing to the SAHEL SYNDROME *Disposition*, is based

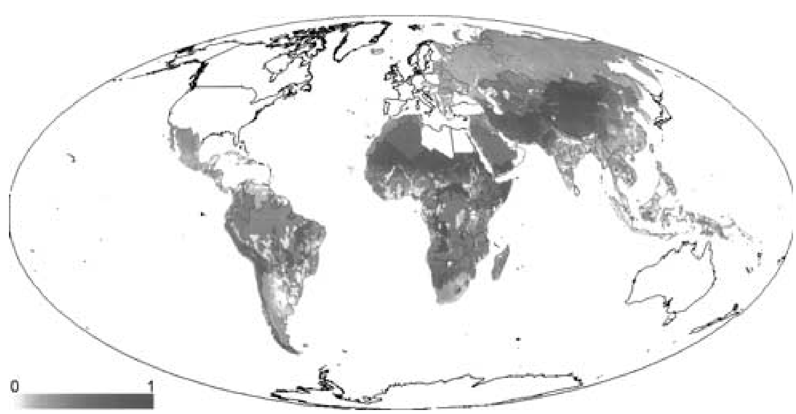

Fig. 5. Disposition towards the SAHEL SYNDROME under the present climate (truth value for "disposition is *high*").

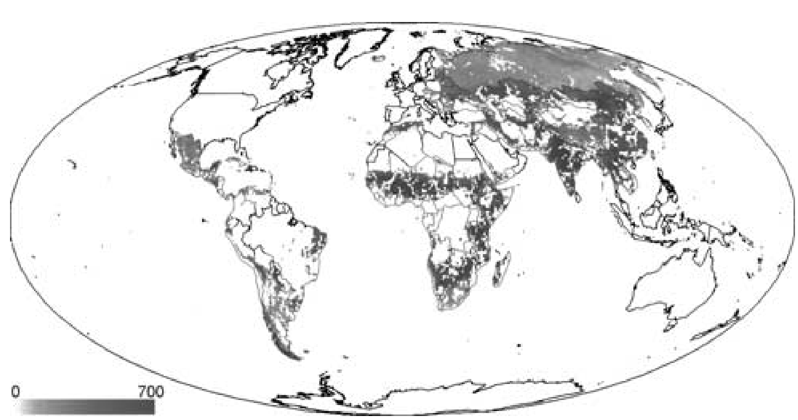

Fig. 6. Climate sensitivity of the disposition towards the SAHEL SYNDROME.

on climate driven models for water availability for irrigation and plant productivity (see Fig. 4).

The next step in Syndrome diagnosis is the determination of the so-called *Intensity*. Here we identify in which regions of the world a particular Syndrome is presently active. The method – strict deduction from the qualitative *Hazardous Functional Pattern* – is closely related to the question of bottom-up identification of functional patterns (see the lower part in Fig. 2) and prognosis of Syndrome development. These methods are discussed in detail in the next section.

3. SYNDROMES II: MODELLING, SPATIAL AND FUNCTIONAL SCALE OF VALIDITY

The approach to formulate a *Syndrome* as presented in the previous section was purely intuitive. Though the assessment of the *Disposition* relates the basic features of a proposed *Syndrome* to data sets or models it is yet unclear whether the "over-cultivation of marginal land" (SAHEL-SYNDROME) actually is a solution of a functional pattern of the Earth System. And if yes, what does this functional pattern actually looks like. Now there is ample literature that relates observations on environmental degradation to this type of resource use, sometimes referred to as Impoverishment-Degradation-Spiral [19, 20]. There are reports on the general behaviour itself as well as on purely social or natural aspects. It is this multitude of observations which suggests that there is a common functional pattern bringing about the experiential types of degradation. The following questions have to be answered, though:

- How can we specify a Hazardous Functional Pattern in more detail, i.e., in terms of the actual relations involved? (This addresses the question of functional "resolution" or scale.)
- How to determine the geographical locations of the occurrence of both, the pattern and the Syndrome?
- How can we verify that this pattern brings about a Syndrome?

The most we can expect from any scheme of "validation" is a non-falsification in the Popperian sense, which is due to the fact that we only can specify necessary conditions for a syndromes activity. The scheme to be used in this process has to take care of the high level of uncertainty of the Earth System's processes.

In the next section, we want to illustrate how these essential questions can be tackled by use of a new qualitative or semi-quantitative modelling approach. The major procedural features of this approach and its differences to conventional, quantitative approaches will be discussed in the subsequent section. There we use the SAHEL-SYNDROME again as a prototypical example how to apply this concept and what to learn from the results.

4. QUALITATIVE DIFFERENTIAL EQUATIONS – FORMALIZING COARSE FUNCTIONAL SCALES

In this section we want to describe the general features of the mathematical tool underlying our methodology. We will use a simple example instead of giving detailed mathematical information which can be found in the respective literature [21]. The example we are going to use is taken from the field of theoretical ecology, in particular population dynamics [22], 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:

$$G = dP/dt = \alpha P(P_m - P), \tag{1}$$

with a climax population P_m and a maximal growth rate $G_m = (\alpha P_m^2)/4$ corresponding to a population P_0. The growth rate exhibits an inverted U-shaped function in dependence of the population P, shown as the full line in the left panel of Figure 7. If we would start with a small population P_1, the growth law in Equation (1) would finally

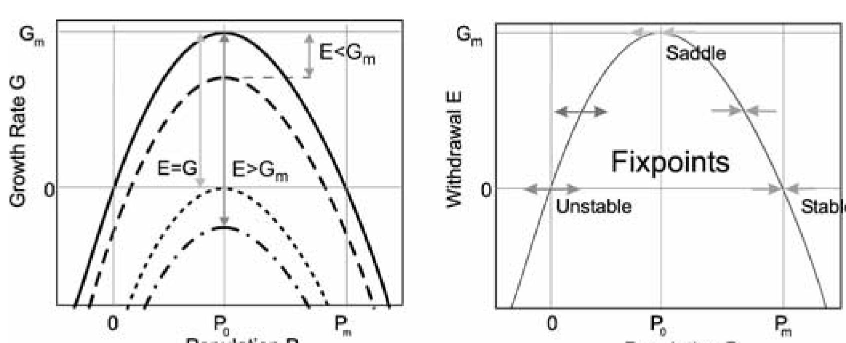

Fig. 7. Basic relation for the didactic model to explain the qualitative modelling approach. If subject to a constant withdrawal E, the U-shaped relation between the population P and the growth rate G gives rise to three different types of behaviour. Starting from the climax state $P = P_m$, the population either stabilises at a level beyond P_0, if the withdrawal is less than G_m (dashed line) or right at P_0 if $E = G_m$ (dotted line). In case of $E > G_m$, the population finally vanishes (dot-dashed line).

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 perturbation to the system in the form of a constant withdrawal E. Therefore the new growth rate is $G' = G - E$. In Figure 7 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 will 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 node, as the equilibrium is unstable. Again, an initial state in the unperturbed climax will lead to a decreasing population ending at half of its original value.
- $E > G_m$ (dot-dashed line): now the withdrawal is too large. No equilibrium exists, i.e., the species will become extinct.

The dynamical behaviour of the system depends on the actual values for the parameters α and P_m, but it seems that the structure of three different behaviour classes is a general property of logistic growth. Therefore these properties should be obtained by a purely qualitative description as well. This would actually 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 at Austin, allows representing the logistic growth in a rather general way:

In the first step, the relevant variables are represented by so-called *landmark-values*, i.e., values where some kind of qualitative change in the relations between these specific variables 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 qualitative differential equations it is not necessary to know the actual values of these landmark-values, but just about 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 values 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 specified either as positive (encoded by $\uparrow$), steady ($^\circ$) or negative ($\downarrow$). In this way, a decreasing population between P_0 and P_m would be written as $((P_0,\ P_m),\ \downarrow)$. 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:

$$((U-\ P\ G\ (P_0\ G_m))(0\ 0)\ (P_m\ 0)). \tag{2}$$

This means: 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 7.

The syntax used in (2) is the one also implemented in the QSIM-software package. By specifying all the relations in this way, 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 pure symbolic manipulation.

A graphical representation of the results is given in Figure 8, which demonstrates that there are three different dynamics which 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. Similarly to the quantitative exercise, there is one case where the population collapses and there are two stable states. However, this result is much more general than the previous information about the quantitative system, since there is much less information about the shape of the functions used. Table 2 summarizes the properties of the qualitative modeling approach by QDEs in comparison with conventional modeling by ordinary differential equations. With respect to the relation of QDEs and the respective classes of ODEs (including members which produce complex dynamics) it is possible to prove that *all* solutions of the ODEs are represented in the qualitative behavior tree generated by the QDE algorithm [21]. Complex ergodic systems result in arbitrary sequences of qualitative states as was proven by Dordant [23].

What do we learn from this kind of qualitative modelling exercise? First of all, we learn that *any* specific U-shaped function with a top-sided vertex which relates population P and its growth rate G brings about one of the three identified 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 T_1 (third column of states in Fig. 8) uniquely determines the final outcome. For example, if at $P = P_0$ the population is still decreasing, it is going to

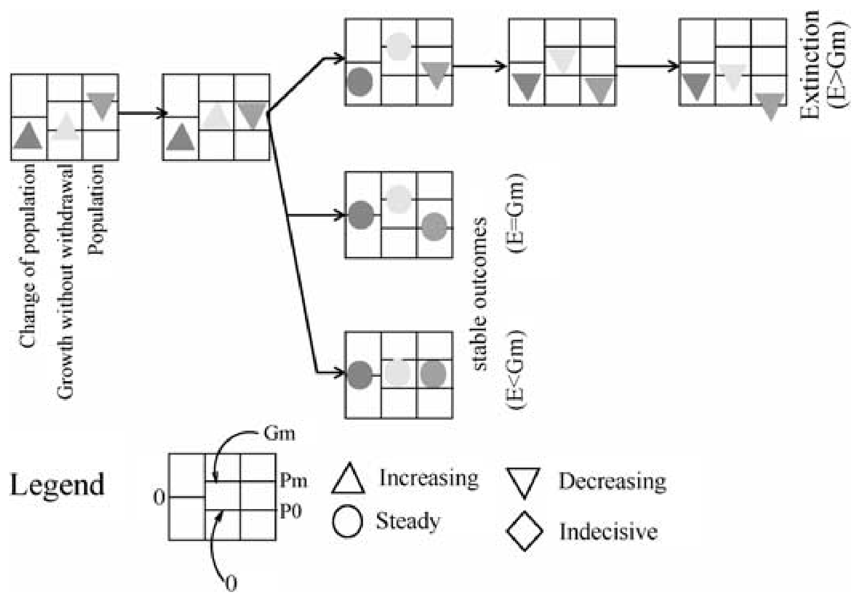

Fig. 8. Qualitative behaviours of the simple didactic model for a general logistic growth of the population dynamics. Each rectangle describes one qualitative state of the system. The black arrows points to possible successor states. Branches of the behaviour tree end either in stable equilibrium states or in ''transition states'' where the trajectory leaves the definition space of the model. For detailed explanation and discussion see text.

Table 2. Comparison of important features of conventional modelling with ordinary differential equations (left) and qualitative modelling (right) using QDEs.

Conventional modelling	Qualitative modelling by QDEs
Numbers on the real axis	• Landmark values specifying distinct values where relations to other variables change qualitatively, e.g., P_0 (see below). • Values to be taken by the variable: landmarks and intervals in between together with the direction of change (↑, ↓, or °).
Real-valued functions modelling the interrelations between the different variables	Qualitative features only, e.g., A is monotonically increasing with B, A is ''U-shaped'' in B with B_0 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 tree of *all* possible solutions compatible with the constraints. Time as a qualitative variable specified in terms of events of qualitative system changes.

vanish in any case – assuming that the structure does not change and no external action is taken. If this dynamical property would describe a real system it might be called ''non-sustainable dynamics'' by the rather general property of irreversible system destruction. In such cases of specific systemic properties the normative aspect of identification of non-sustainable trajectories is less important compared with situations where pure external valuation is applied.

So far, purely qualitative modelling has been described. However, if there is also some quantitative information available, it seems to be sensible to make use of it. Quantitative information can come in two different ways:

- Quantitative upper and lower limits for some or all of the landmarks might be available.
- Some quantitative information about the functions appearing in the QDE, e.g., in the form of upper and lower envelopes might be at hand.

In our example, one possibility would be that intervals for the amount of harvesting and for the maximum growth rate are known. If, e.g., for all values compatible with those intervals the maximum growth rate G_m is larger than the amount of harvesting E (e.g., $E = (12,14)$, $G_m = (15,30)$), then the population collapse behaviour can be ruled out.

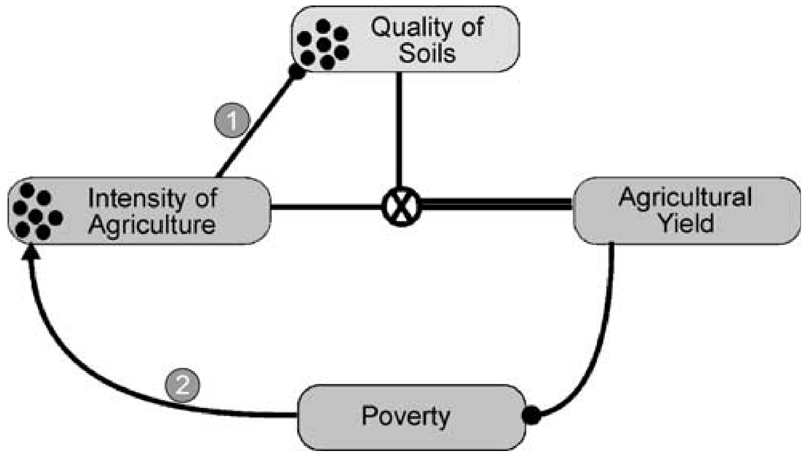

Fig. 9. Core mechanism of the original version of the SAHEL-SYNDROME. The symbols attached to the connecting lines uniquely encode qualitative relations as used within the concept of qualitative differential equations (QDEs). Their meaning is explained in the Appendix.

Additionally to the possibility of excluding some behaviours, interval analysis works also the other way round: Depending on the qualitative behaviour, the intervals can be refined. If, for instance, the population collapse behaviour is possible, then under the condition that this behaviour appeared, one knows that the lower bound of E must be larger or equal to the lower bound of G_m.

The numerical difficulty increases, of course, drastically if we change from topologic time to metric time, i.e., if one wants to know something about the quantitative meaning of the stages in the dynamics. Apart from very direct interval arithmetic approximations that can yield crude estimates based on the mean value theorem, there are several different methods to tackle this problem which is very similar to the deduction of the reachable set of a differential inclusion ([24]; for applications within Global Change research see Tóth et al. [25], Petschel-Held et al. [26] and Bruckner [27]). This is an area of intensive current research, where we test a Hamilton-Jacobi-type method [28] and a level-set approach.

4.1. General Hazardous Functional Patterns and Detailed Local Case Studies

In its original version, the SAHEL-SYNDROME was designed to describe the situation for pure subsistence agriculture on marginal sites [8, 15, 17, 18]. The smallholder agriculturalists to be described by the mechanism (Fig. 9) do not have any alternative means of income and are thus enforced to use and finally overuse the marginal natural resources of their environment. This includes pasturing, farming, collection of firewood, etc. Due to the lack of alternatives the smallholders intensify their agricultural activity in case of a reduced agricultural yield, i.e., increased poverty (line 2 in Fig. 9). However, these statements do not describe mechanisms, but solely outline observed developments over time. From our point of view, mechanisms are represented by more general statements on relations between variables. In case of poverty and intensification such a relation might have the form: the higher poverty is the higher is intensification.[1] The reason why one would like to do so is obvious: if we use the generalised mechanism we do not only have information on what will happen if poverty is increasing, but also what occurs if it is decreasing! This will play an important role when assessing the different dynamical behaviours within a functional pattern. The important point here is that we do not exactly know how this relation between *poverty* and *intensification of agriculture* looks like, or even: we do not claim that this relation is quantitatively the same in different regions. Of course, such a potential difference holds also for the other relations, e.g., the increased loss of soil quality due to increased agricultural activities (on marginal sites). In the latter case, the idea of regional ‘‘difference in similarity’’ can be illustrated as follows.

The ‘‘geographer’s argument’’ states that every two regions are different concerning their specific form of human-nature interactions. Does this statement actually mean that no two regions share any common features? Certainly not, as otherwise any attempt to understand human use of natural resources would have to start all over again for each newly investigated region, and rather general theoretical claims concerning, e.g., the relation between the length of the fallow period and soil fertility would not be applicable. We thus assume that the geographer’s argument might well be true if applied to ‘‘quantities,’’ but that it not necessarily applies to qualities. In other words, the relationship between ‘‘fallow period’’ and ‘‘loss of fertility,’’ measured, say, in nitrogen loss in kg/year, might be quadratic in one region and logarithmic in another. Yet it is monotonously increasing in both! In this sense both

[1]Here we neglect the fact that too high levels of poverty are actually related to a decrease of intensification due to a loss of labour force and capital, e.g., seeds, stock, etc.

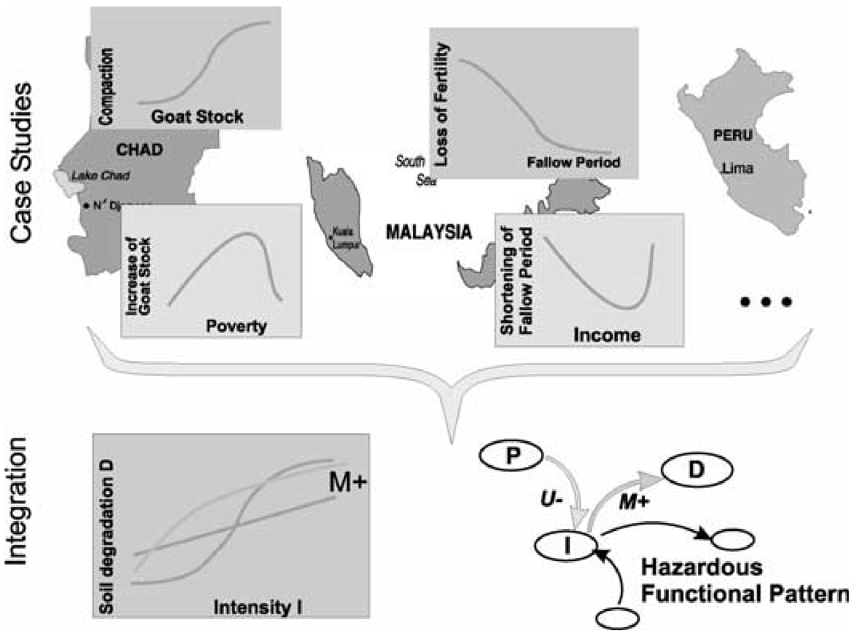

Fig. 10. Scheme of generalisation used to formulate a class of civilisation-nature interactions. Case studies might be used to specify the regionally valid relations between relevant variables. Abstracting these variables into more general concepts, e.g., Intensity or Soil Degradation, are then used to specify qualitative relations between the abstracted variables. In the example given the qualitative relations, indicated by the notions U- and M+ in the cause-effect scheme on the lower right hand side, contains the (hypothetical) situation in Chad as well as in Malaysia and possibly Peru.

regions belong to the same class: they exhibit a monotonously increasing relation between "fallow period" and "loss of fertility."

This idea of class identification can be extended by abstracting the rather specific variable "fallow period" to the more general notion of *intensity of agriculture*. Yet, this generalised, abstracted variable comprises not only the issue of fallowing, but also, e.g., of life stock density, fertiliser input, ploughing, etc. Analogously, one can use the notion of *soil degradation* as an abstraction of "loss of fertility." These abstractions have to be order preserving, i.e., two regions with a certain order of fertility loss, say region 1 has a higher loss than region 2, resume this order within the abstracted variable.[2] Thus all the regions belonging to the class with a monotonous increase between fallow period and loss of fertility also belong to the class with the same type of relation between *intensity of agriculture* and *rate of soil degradation*. Yet this class contains also regions where a monotonously increasing relation between, say, goat stock density and soil compaction is valid. Line 1 in Figure 9 exactly encodes this type of relation which formally can be treated in this generality within the concept of qualitative differential equations (QDEs).

This idea of generalisation and class formation, which is summarised in Figure 10, lies behind the formalisation of a *Hazardous Functional Pattern*. In contrast to previous interpretations [29], the network of qualitative, general relations depicted in Figure 9 does not directly represent a *Syndrome*,[3] but rather a model of a *Hazardous Functional Pattern*, which might bring about a non-sustainable development. As such, this specification is completely legitimate. The question is whether one can formulate a set of qualitative models, and thus classes, which are:

- detailed enough to include important details of the processes involved, but which are
- general enough to incorporate all the important aspects of sustainable development into a limited set of models.

Both questions are related to each other by the issue of validation: can we find enough regions in the world which belong to this class. The direct proof – we know all the mechanisms of a region in sufficient detail to conclude whether it is a member of the class or not – will be exceptional. Therefore an indirect approach is chosen whose scheme is sketched in Figure 11. On the one hand the formal analysis within the QDE-concept allows to specify all qualitative time behaviours of the variables which are compatible with the functional pattern (step 4 in Fig. 11). On the other hand, there are countless observations – quantitative and qualitative. The latter might comprise of statements

[2]In case of more contributions to soil degradation one might use soil degradation as a (weighted) aggregate of the various aspects. Then the mapping from the weighted aggregate to the abstracted variable has to preserve the order.

[3]Formally, a qualitative differential equation represents a class of ordinary differential equations.

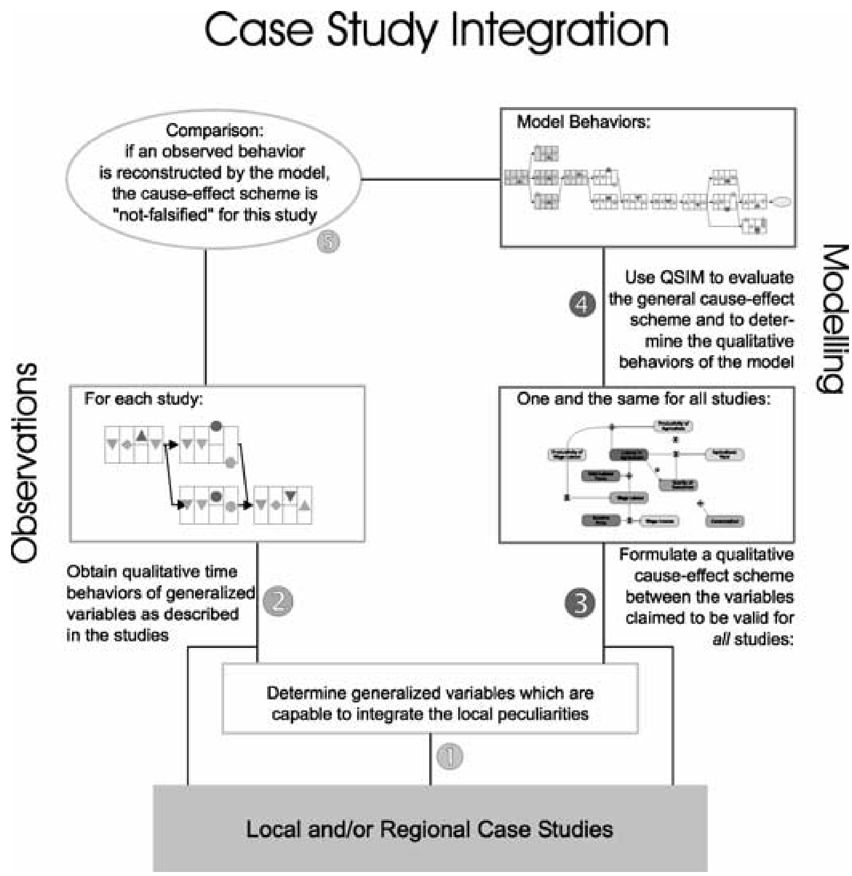

Fig. 11. General scheme of case study integration into a common class of causes and effects.

like "the landslide frequency has increased since the 1950s, but declined in recent years." Thus, if an observation is reconstructed by at least one of the model behaviours (step 5 in Fig. 11), the actual mechanisms in the region considered are free of contradiction with the pattern described by the model. We might say that the applicability of the pattern and its mechanisms for this region is not invalidated. If this can be shown for enough regions, we might well claim that the pattern of mechanisms is globally relevant.

A validation in this sense was performed in Petschel-Held et al. [30] where we could show that a functional pattern similar to the Sahel-HFP was able to reproduce the main qualitative observations of (almost) all case studies from the DFG-Programme "Environmental Perception and Coping Strategies in Endangered Ecosystems of the Developing World."

This iterative procedure of formulation and validation of functional patterns is structurally very similar to the concept of "*strategic cyclical scaling*" (SCS) as formulated by Root and Schneider [1]. They propose a continuous cycling between large-scale studies (dealing with correlation of macro-variables) and small-scale studies (dealing with the investigation of mechanisms) to obtain at least a macro-theory based on sound causal relationships instead of statistical coincidence (which is the condition for any prognostic ability).

In our procedure of case study integration the functional large-scale or marco-level is the general *Hazardous Functional Pattern* consisting of aggregated state variables (*Symptoms*) and their very generally characterised interactions. Switching iteratively between "large-scale-studies" (i.e., the construction and mathematical evaluation of the actual HFP hypothesis) and "small-scale-studies" (i.e., the systematic interpretation of different aspects of local case studies resulting in corrections of the large scale hypothesis) yields at least for the given scientific knowledge a consistent functional "macro-pattern." The hypothesization of a HFP by carefully interpreting detailed case studies is sometimes also referred to as process tracing which is now of increasing relevance within the political sciences [31, 32].

Note that we do not identify the derived functional pattern as a *Syndrome* per se. The difference is that a *Syndrome* is understood as a clinical picture of civilisation-nature interaction, whereas the qualitatively defined patterns of interactions are assumed to have more general validity. We now demonstrate, how this more general formulation of patterns can bring about a *Syndrome*. This is strongly related to the question how a *Syndrome* is actually engendered.

Example: Time Behaviour of the Local Sahel HFP.

The cause-effect scheme of Figure 9 already contains most of the information needed by QSIM for a formal analysis. The qualitative multiplication between agricultural intensity and quality of soils to obtain the yield simply states:

1. If one of the two factors is zero then the qualitative product (yield) is equal to zero, and
2. the directions of change are analysed according to the product rule of differential calculus, i.e., $(uv)' = u'v + uv'$.

Yet some more information is added to the scheme. In particular, we specify two landmark values, "maximal sustainable" (*ms*) and "existential" (*ex*) for the intensity of agriculture and poverty, respectively. For the intensity we assume that for values less than *ms* soils can regenerate, whereas for values larger than *ms* soil degradation is taking place. Similarly for poverty: if it is below *ex* no intensification of agriculture is performed. This takes place for poverty in excess of the existential level only.

Figure 12 depicts the qualitative time behaviours of the relevant variables within the core mechanism of the Sahel-HFP as displayed in Figure 9. We have chosen as the initial condition an environmentally positive, i.e., increasing soil quality, but socially stressed situation, i.e., existential poverty. This stress has not yet led to a massive increase in agricultural intensity, i.e., intensity is below its maximal sustainable level. This situation corresponds to the case where a change in the terms of trade, population growth, social marginalisation, etc. have induced high levels of poverty.

The behaviour tree in Figure 12 represents a restricted projection of possible evolutions within the Sahel HFP of interaction mechanisms between humankind and nature. It can be seen that there exist basically four classes of possible outcomes of the time evolution of this functional pattern. An outcome is defined as a final state in the model and is realised either as a fixed point (or quiescent state as it is called within QSIM) or as a transition state where one or more variables leave the domain for which the model is valid. The latter is, e.g., true for the states indicated as *Resource Focused* in Figure 12, where the quality of soil reaches its "natural" level and is still increasing: the model does not give any specification what is going to happen afterwards. These outcomes can only be expected in case of rather productive soils with a rapid regeneration rate.

The other two types of transition states are described as *Acceptable* and *Catastrophic*. In the first case agriculture is on a low level or abandoned and soils can regenerate because the income is still large enough, i.e., poverty remains below the existential level. Again this is due to productive places, but it might also be realised using highly efficient and soil

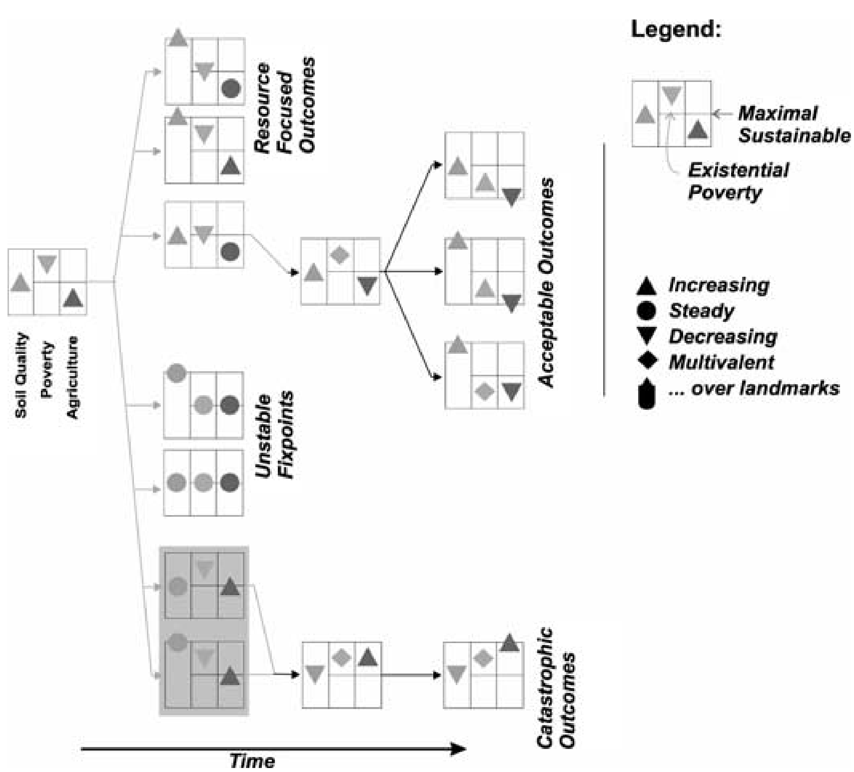

Fig. 12. "Behaviour tree" for the original Sahel HFP of causes and effects. Boxes and arrows indicate the qualitative states as explained by the legend on the right hand side. Time runs from left to right. Note that in some cases more than one successor is possible, e.g., for the initial state on the QSIM identifies seven possible successor states from the model.

preserving agricultural techniques. Formally this corresponds to a value of *ms* high enough not to be reached within the simulation.[4]

The outcome characterised as catastrophic and the dynamic behaviour leading to it actually represent what is understood as the SAHEL-SYNDROME: existential poverty leads to a lasting intensification which strongly damages the natural resources. Due to this damage there is no chance to increase the income, i.e., reduce the poverty, sufficiently. The cycle starts all over again . . .

Taking the catastrophic outcomes as the *Syndrome* as such, we can assess the question how it is engendered. If we look at the two intermediate states (shaded within the tree), we observe that the *Syndrome* evolves from the (neutral) initial state if the intensity of agriculture reaches the landmark value *ms*, before poverty is reduced below its existential level. Though this can happen purely due to the increase of the intensity, it might well be enforced by natural events like droughts or floods, which lower the actual value of *ms*: Agricultural activities being sustainable before the drought might be damaging to the natural resources in case of the extreme event. This rather detailed discussion of the model results of the simple Sahel HFP should illustrate the type of results produced by a qualitative model as well as its applicability.

4.2. The Extended Sahel HFP and Spatial Distribution of Time Behaviours

With the introduction of the HFP concept some new forms of spatial aspects have to be considered compared to traditional modelling. Let us first assume that the HFP consists only of local interactions between the contributing trends (as in the example given in the preceding paragraph) and that it is separated from further HFPs (which must not be the case: the Favela-HFP may, e.g., interact closely with the Sahel-HFP via migration). Now there may be a large region where the general HFP is valid, but in different sub-regions different trajectories (branches of the behaviour tree) may be realized. We will call the subclass of the quantitative differential equations (with respect to the QDE) which produce a particular qualitative behaviour "*Detailed Functional Pattern*" (DFP). It is important to note that a DFP is only specified by its behaviour and cannot be described in terms of a more detailed qualitative cause-effect scheme (at least for the time being; methods proceed). This heterogeneous time behaviour will occur when the general mechanism is valid all over the region but the detailed realizations of the symptoms and interactions differ significantly (due to different natural conditions, cultural or technological particularities, etc.). This may, e.g., lead to different outcomes of the race between yield enhancement and soil degradation by intensification measures. Therefore, the appropriate spatial scale of observation is that of a single DFP, otherwise syndromatic trajectories may be masked by adjacent regions which perform acceptable branches of the same HFP.

In a preliminary study we investigated the behaviour of the simple Sahel HFP when a non-local interaction is introduced. Here we chose the land-use → regional climate interaction via change in albedo and evapotranspiration – an effect which is discussed controversially in the literature as a reason for the acceleration of desertification processes (e.g., Voortman [33] and Le Houérou [34]). To include this hypothesis in the Sahel HFP, we assume that the state of resource degradation in all subregions determine the change of the common regional climate which then influences the yield by decreased rainfall etc. Here we can use the adiabatic approximation due to the fast adaptation of regional climate to the surface properties compared with the long time scale of, e.g., soil degradation processes. This results in a coupling by a simple qualitative function relating resource degradation with regional climate. The coupling is formulated for two regions by introducing an additional "macro"-variable, "Regional Climate," which is an increasing function of the resource quality (here represented by "Quality of Soils") in both regions. This macro-variable feeds back on both local yields which now depend on the local resource quality, the local agricultural activity and the regional climate influence. The extended functional pattern is displayed in Figure 13 (for the explicit mathematical definition of the different relations see the Appendix).

We want to remark one particularity of the introduced non-local interaction: In case of two similar sub-regions (identical DFPs with respect to the local model discussed in the previous section), identical initial conditions and symmetrical non-local interaction, the resulting time behaviour for both regions is identical and can be described with the local model. This is possible because in this case the climate interaction can be assumed as integrated in the monotonic relation between resource quality and yield (see Fig. 13). Therefore the proposed enhancement of the pattern by a non-local interaction is the structurally most moderate step. This is in contrast to enhancements implying new relations between the variables which are not already represented in the local dynamics.

Evaluating the functional pattern in Figure 13 using the QSIM-algorithm yields the behavior-tree for one of the two sub-regions (assuming appropriate behavior of the second region) as displayed in Figure 14. Due to the qualitative structure of the non-local interaction the result for one sub-region would not change for an arbitrary number of coupled sub-regions. To keep the result more transparent we omitted the "resource focussed" states

[4]This is a qualitative argument, though. The simulation is purely symbolic and does not assume any numbers, neither for the variables nor for the landmarks. It just assumes their existence and constancy.

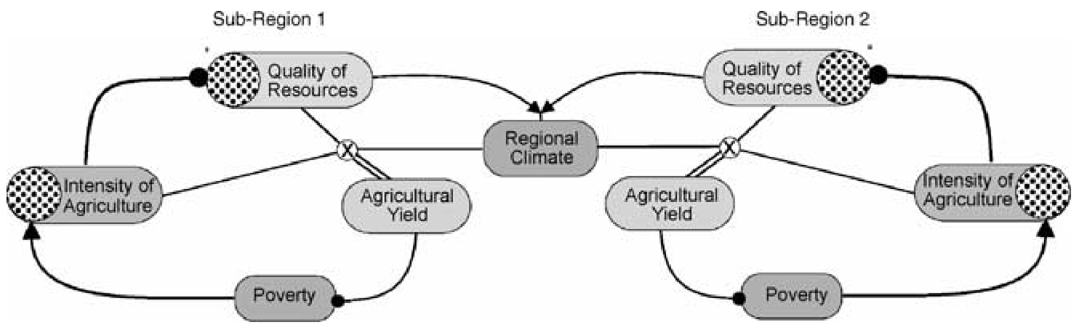

Fig. 13. Enhancement of the simple Sahel-HFP introducing two sub-regions coupled by a non-local landcover-climate interaction (for the definition of relations see Appendix).

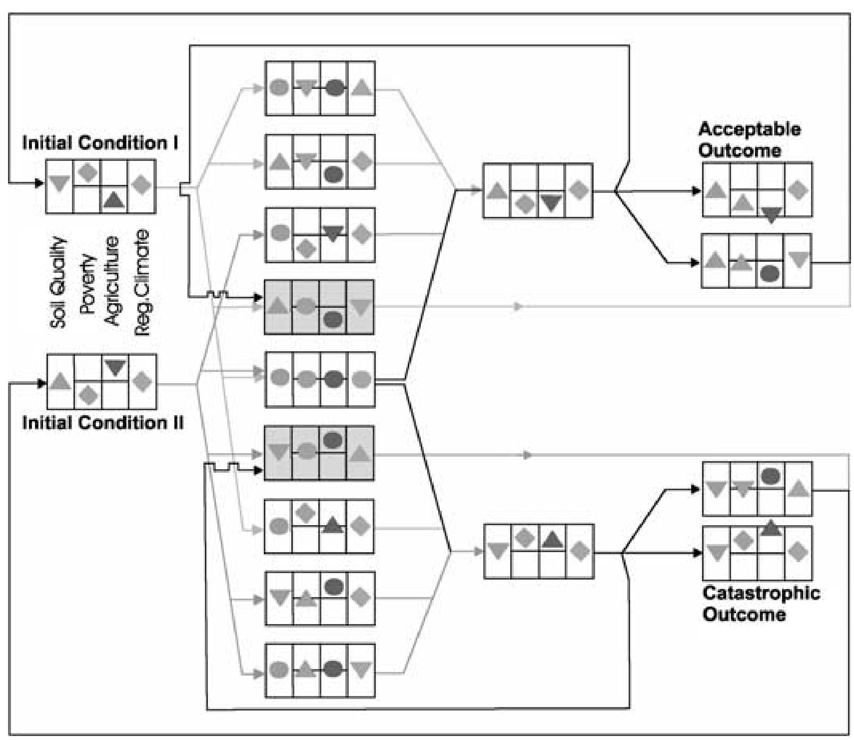

Fig. 14. Resulting behavior tree for the enhanced Sahel HFP (two sub-regions coupled by a non-local landcover-climate interaction) for one of the sub-regions. For a detailed legend see Figure 12.

(see Fig. 12) which are somewhat unrealistic and observe that:

- all trajectories which are possible in the case of only local interactions (see Fig. 12) can still be realized in each region,
- some new (cyclic) behaviours can occur, therefore
- ‘‘secure’’ states in the case of the local HFP (i.e., non-bifurcating trajectory ending in an acceptable outcome) may become insecure (shifting to the non-sustainable paths) in the case of strong resource degradation in the adjacent region.

So we can conclude that in case of increasing evidence of the land-use/regional climate interaction as a relevant aspect of the degradation-impoverishment mechanisms the enhancement of the simple local Sahel HFP with respect to non-local effects is necessary because otherwise:

- the identification of a region as governed by the pattern will fail in several cases, and
- misleading conclusions about further possible qualitative developments might be drawn resulting in wrong policy advice.

The model enhancement explained above gives an example for one further iteration in the development of sound HFPs as elements of understanding GC on an intermediate functional scale.

5. CONCLUDING REMARKS

In Section 2 a hypothetical, "idealistic deduction" of the concepts of the Syndrome approach was performed (Fig. 1) in order to illustrate how the aspects of spatial and temporal scale are closely related to the detail of functional description (functional scale) of Global Change. The decomposition of the complex Earth System into *Hazardous Functional Patterns* takes these aspects into account from the beginning (formal methods as canonical transformation and adiabatic approximation were mentioned).

In a next step a more inductive method to obtain HFPs on an *intermediate functional scale* is introduced and a set of 16 *Syndromes* (Table 1) as non-sustainable time developments of the HFPs is given. As an example for the application of the adiabatic approximation to extract the dynamic properties relevant for GC the Disposition concept is explained and applied to the SAHEL SYNDROME (Figs. 4 & 5).

In Section 3 we give a more formal method how these HFPs can be obtained from a large number of detailed case studies (Fig. 11). An iterative procedure of case study generalisation which is structurally similar to the Strategic Cyclic Scaling approach [1] is introduced. A central concept in this systematised procedure to obtain HFPs are qualitative differential equations (QDEs): They allow to subsume different forms of interactions as observed in different case studies under classes of relations (characterised by general properties like monotony). As "didactic" example for the application of this concept a simple population dynamics under constant yield is discussed (Figs. 7 & 8) and a systematic comparison between usual modelling concepts and the QDE concept is given – including the "costs" of modelling on a more coarse functional scale in terms of loss of detail in prognosis (Table 2).

Then two versions of the Sahel-HFP were elaborated:

i. A first version based on local interactions only (Fig. 9), illustrating in detail the aspect of *functional scaling* in the Syndrome concept (Fig. 10). On the level of the obtained intermediate functional scale sustainable and non-sustainable qualitative trajectories could be identified (Fig. 12, for a detailed discussion of policy option development based on this results see Petschel et al. [15, 30]). Additionally we could formulate rules for the identification of appropriate scales of observation which are defined by the spatial extent of *Detailed Functional Patterns* (DFPs) which characterise the conditions for the validity of a single trajectory of the HFP.
ii. An enhanced version of (i) which considers an additional non-local interaction. Here we included an interaction between land-cover and regional climate (Fig. 13) which is discussed controversially as one reason for desertification processes. As a result we obtained that all trajectories which were possible in the case of only local interactions still could be realised in each sub-region but that some new (cyclic) behaviours could occur. Therefore "secure" states in the case of the local HFP could become insecure. This enhancement is one iteration in the general scheme of integration displayed in Figure 11 – new evidence from local and regional case studies (step 1) suggests the relevance of the land-cover/local climate interaction based on observations of relevant variables (step 2). The HFP is modified according to the new functional hypothesis (step 3) and evaluated with respect to all compatible dynamic behaviours (step 4) which have then to be compared with the available observations from all case studies (step 5).

The results of the enhanced model suggest a further facet of the Syndromes Approach to Scaling besides the functional scaling/generalisation aspect already discussed: the approach might be used to determine a hierarchy of non-local interactions with respect to their influence on the dynamics of the local sub-models:

- the preservation of the "local" trajectories without new behaviours (as in the given example for particular conditions)
- the preservation of the "local" trajectories and appearance of new behaviours (as in the given example in general)
- the generation of a completely new behaviour tree

In the first case the added non-local interaction produces no new dynamic behaviours – the local analysis is sufficient. In the second case two different versions have to be considered. The new behaviours may mix up former, local sustainable and non-sustainable trajectories (as in the example) or not. In the latter case parts of the local analysis can be maintained – otherwise the application of the local analysis leads to severe misinterpretations with respect to sustainability questions. In the third case a totally new analysis is necessary.

This classification of additional complexity induced by non-local interactions shows that the concept of qualitative differential equations in the framework of HFP generation may also contribute to this particular question of scaling.

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APPENDIX A: IMPORTANT TERMS OF THE SYNDROME CONCEPT

Symptoms:
spatial/functional aggregates of detailed variables describing Global Change which allow for systematization of their relations

Hazardous Functional Patterns (HFPs):
sub-systems (Symptoms and their functional relations) of the global system producing non-sustainable trajectories (among others)

Syndromes:
typical non-sustainable trajectories/development paths of sub-systems of the global system (HFPs)

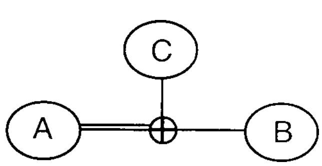
Detailed Functional Patterns (DFPs):
concretization of a HFP, producing exclusively a class of non-sustainable trajectories (Syndrome)

Disposition towards a Syndrome:
degree to which the conditions for the syndrome's most important mechanisms and interactions are fulfilled

Functional Scale:
detail of functional description (degree of consideration of detailed mechanisms and related variables) – related to spatio-temporal scale, but not identical

APPENDIX B: SYMBOLS USED FOR THE GRAPHICAL REPRESENTATION OF QUALITATIVE MODELS

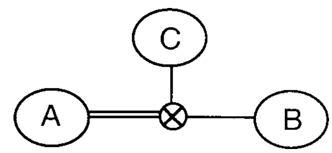
In order to have an intuitively simple to understand way to describe qualitative models, we introduce a few special symbols to denote the functional relationships in a qualitative model. qdir stands here for the qualitative direction of a variable, i.e., increasing/steady/decreasing/unknown and qmag denotes its qualitative magnitude, i.e., its state relative to qualitatively important landmark values (e.g., 0).



This encodes a qualitative addition of B and C to yield A. A qualitative addition is specified, e.g., by the following properties:

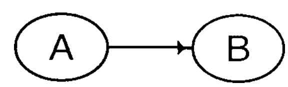
- The directions of change are added, i.e., if qdir(C) > 0 and qdir(B) > 0 so is qdir(A); yet if qdir(C) > 0 and qdir(B) < 0 then qdir(A) can be either positive, negative, or zero.
- If qmag(B) = 0 and qmag(C) = 0 so is qmag(A) = 0.
- If qmag(B) = 0 and qmag(C) ≠ 0 then qmag(A) = qmag(C).

There is no qualitative subtraction. Subtraction, i.e., A = B − C is expressed as a qualitative addition, i.e., A + C = B.



This encodes a qualitative multiplication of B and C to yield A, i.e.:

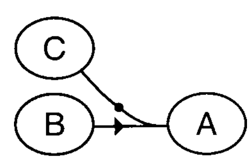
- The directions of change combine according to the chain rule of differential calculus, i.e., qdir(A) = qmag(B) . qdir(C) + qmag(C) . qdir(B).
- If qmag(B) = 0 or qmag(C) = 0 so is qmag(A) = 0.



B is a monotonic function of A, i.e., among others, if A increase then also B increases. This corresponds to the condition:

$$\frac{\partial B}{\partial A} > 0.$$

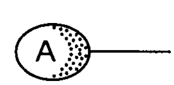
In case of a bulleted connection line instead of the arrow we have a negative sign for the partial derivative.



This is a multivariate-constraint corresponding to the relations

$$\frac{\partial A}{\partial B} > 0, \qquad \frac{\partial A}{\partial C} < 0.$$

Here, a bullet always indicates a negative partial derivative, whereas the arrow-like symbol encodes a positive partial derivative.



The constraint does not relate to the state variable A itself, but rather to its rate of change, i.e., dA/dt.