Syndromes of Global Change: a qualitative modelling approach to assist global environmental management

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A novel transdisciplinary approach to investigate Global Change (GC) is presented. The approach rests on the decomposition of the intrigue dynamics of GC into patterns of civilization–nature interactions ("syndromes") by an iterative scientific process of observations, data and system theoretical analyses, and modelling attempts. We illustrate the approach by a detailed analysis of the Sahel Syndrome, which describes the rural poverty driven overuse of natural resources. The investigation is performed by (i) identifying relevant "symptoms" and interlinkages which are characteristics for this pattern, and (ii) a qualitative model representing the internal dynamics of the essential flywheel. The geographical patchwork of the regions affected by the syndrome which is obtained by global data analysis, proves the high global relevance of this pattern. The qualitative model is employed for an evaluation of basic policy strategies debated in the context of rural poverty driven environmental degradation. It turns out that a mixed policy of combating poverty and introducing soil preserving agricultural techniques and practices is most promising to tackle the syndrome dynamics.

Keywords: global change, environmental policy, rural poverty, soil degradation, qualitative modelling

1. Introduction: Global Change

The variety of articles in this volume perfectly illustrates the broad range of questions and problems encountered by Global Change (GC) research. The intriguing complex of issues includes (see, e.g., [43,61])

- modification of the physico-chemical composition of the atmosphere,
- soil degradation of all types,
- reduction of natural ecosystems by area and quality, implying significant loss of biodiversity,
- pollution of freshwater resources and coastal zones,
- global dissemination of allochthonous species, pests and disease vectors,
- population growth enhancing transboundary migration and crowding in ill-managed mega-cities,
- amplification of world-wide disparities regarding income, sanitation and education – not to speak of "imponderables" like human dignity.

It is the highly interrelated entirety of these problems which distinguishes the current development as a crisis unique in mankind's history. In recent years policy and science have increasingly realized the urgency of resolving this crisis which has brought forth the scintillating idea of *sustainable development* as an ideal of the world to be (see, e.g., [10,43,50,61]). Yet neither the ideal itself nor the paths to achieve it are sufficiently defined, clarified, or understood [49].

The methodologies of Global Change related research can basically be embedded into a triangle:[1]

1. The first corner of the triangle is constituted by rather disciplinary research heading for the identification of basic processes, functional properties and/or first principles of more or less well separated subsystems of the Earth System. Examples include investigations on physiological processes within single plants (see, e.g., [53]), on demographic processes and perspectives [12], or studies on economic development (see, e.g., [48]). This kind of research is of great importance for the understanding of basic processes relevant to GC.

2. There are models with a highly intersectoral and interdisciplinary subject. In the extreme these models do not use functional relationships obtained by disciplinary studies described in the previous paragraph. Instead, they rest on highly parametrized ad hoc functions, e.g., adopted by sophisticated methods of stochastic regression. One of the most prominent representatives of this class, though probably not the most extreme, is the WORLD3 model [35]. More recently, models similar in scope, e.g., the IMAGE models [1,2], have moved much more towards the "functional corner" of the triangle. Some of these global models actually start from the functional perspective (see, e.g., [15,19,42]). Global models of this type are highly relevant in understanding the processes on the global scale, e.g., climate change, global vegetation, etc.

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[1] There is, of course, no unique way to classify this wide field of scientific endeavours. The typology given here is most useful to clarify the epistemological background of our approach.

3. Finally, there is a vast number of case and field studies (from the library-filling literature see, for example, [6,21]) disclosing a broad collection of insights on processes on the civilization–nature interface. Though mostly regional or local in scale, these studies allow basic aspects of human impacts and consequences of environmental changes to be identified. In some cases the environmental processes are systematically linked to the globe, e.g., climate change [11] or reduction of stratospheric ozone [60], in other cases the linkage is cumulative like soil degradation [41] or social and ecological impacts of large dams [33].

Though there is an increasing basis of knowledge in all three categories, the comprehension of the underlying structures inducing Global Change is still limited. The syndrome approach propagated here is designed to improve this comprehension by incorporating cognitions and knowledge from all of these sources. This cannot be achieved without sacrificing quantitative rigour in favour of *qualitative*, *intuitive*, and *typifying* aspects. The basic idea is not to describe Global Change by regions or sectors, but by *archetypical, dynamic, co-evolution patterns of civilization–nature interaction* which we call *syndromes*.

What is the major property of this kind of patterns which distinguishes them from other entities of Global Change, like models or scenarios? As dynamical objects we can consider them as different sub-dynamics of Global Change which are endowed with a far reaching independence of each other. This does not mean that they are *completely* independent. Yet it is assumed that the interlinkage is as weak as to allow comprehensively isolated analyses of each single pattern. The interrelation between syndromes is mapable onto abstractions of each other, i.e., an external syndrome is assessed by a single variable within the analyses or the modelling attempt. It is this basic property which singles out the idea of syndromes as patterns of Global Change.

These patterns can be formalized qualitatively and their dynamic is modelled by use of *qualitative differential equations* [24]. It is the subject of this article to discuss this concept, both in its generality (section 2) and in its specific realization illustrated for the SAHEL SYNDROME.[2] The paper intends to extend the ideas presented in an earlier paper [51] and the first outlines of the concept sketched by the German Advisory Council on Global Change [16,17]. As we have to distinguish between concepts of syndrome *diagnosis* (section 3) and dynamic syndrome *modelling* (section 4), we independently elaborate on these methods in two different sections. Whereas the first relates to a detailed analysis of the status quo, the second is more oriented towards an evaluation of options of global environmental management. In section 5 we conclude with a summary and a general outlook.

[2] To distinguish specific syndromes from syndromes as a concept, we henceforth indicate specific syndromes by typesetting their names in SMALL CAPITALS. This automatically implies a cross-referencing to table 2.

2. The conceptual outline

As mentioned before, syndromes are tentatively defined as archetypical patterns of civilization–nature interaction. Nevertheless, it is probably impossible to derive syndromes *formally* from an information base which is in the first instance unstructured. Though one might think of obtaining these patterns by some type of cluster analysis of quantitative data seemingly relevant to Global Change or by a (block-)diagonalization of a general, yet fictitious, matrix encoding interactions relevant to GC, the results would be of limited use only. One main defect is that the very nature of the underlying processes within and between syndromes would hardly be identifiable. Another important deficiency would be the limited feasibility of including qualitative information into the analysis. Altogether this implies that it is preferable to analyse syndromes *inductively* by explicitly using hard (data, theories, etc.) and soft knowledge (expert judgements, intuition, etc.). These contrary procedures may be compared to the identification of relevant general weather situations by methods of synoptical meteorology versus using various clustering techniques of hard quantitative data, e.g., temperature, air pressure, or wind.

The baseline of the discursive processes of syndrome specification is the human ability or even propensity to group and/or classify his or her observations. Within the attempt to rigorously identify patterns of civilization–nature interactions this implies (a) that the typifications of a large (and hopefully increasing) number of scientists and/or experts have to be synchronized, and (b) that the results are continuously open to corrections based on new observations. In this sense observations include case studies, model results, global data monitoring or even theoretical knowledge. The scientific process might be compared to the history of medicine apart from its mechanistic sub-discipline of molecular biology [13] (note that our terminology to some extent is loaned from medicine) or to the still successful field of synoptic meteorology. It is probably an excellent example of scientific progress by hermeneutic cycle.

The inductive character of syndrome analysis has some important implications, as the approach does not actually call for validation, but rather that its explanatory power be checked. As will be demonstrated, our analyses within syndrome *diagnosis* are first of all alternative interpretations of data: putting together known data in a new systematic manner allows aggregated indicators for various syndrome properties to be obtained. We do not restrict ourselves to measured data directly obtained by an instrument or a census, but also rely on model results, e.g., from global vegetation or hydrological models [9] or qualitative data like expert interviews. This suggests that the different measures, e.g., indicating the activity of a syndrome in a certain region or the proneness for a syndrome, cannot be validated directly. Moreover, there is no instrument which would allow us directly to "measure" these syndrome properties for comparison. Instead, the quality of the overall syndrome diagnosis has to be graded by its explanatory power for the entire variety of core problems of Global Change [17]. The regional and temporal patterns of these core problems, e.g., soil degradation, climate change, endangerment of food supply, etc., have to be explained simultaneously by the corresponding combination of a limited number of syndromes. This points to the necessity for a more or less complete analysis of syndromes in order to allow this overall validation scheme to be carried out (for a first attempt concerning soil degradation see [51]). In addition, each regionally explicit single syndrome diagnosis can be checked by its plausibility and by a comparison with more qualitative information, e.g., direct field studies, global reviews on certain aspects of the syndrome, etc. [9].

We have to underline that syndromes are not independent of each other. There is a wide variety of coupling mechanisms between them which at the end of the day have to be taken into account for a complete analysis of GC [51]. Yet in this paper we concentrate on a single syndrome which represents the starting phase of the medium term endeavour of syndrome analysis of Global Change.

2.1. Basic vocabulary I: symptoms

There is a huge variety of processes, facets, and phenomena to be taken into account when analysing Global Change. A major problem is that the concepts used in one discipline are often understood differently in another field. It is therefore important for any Global Change research to consolidate a common language across the disciplines. In our context we have adopted the notion of *symptoms* of Global Change from the German Advisory Council on Global Change [16]. This notion has become apparent as a good common ground for the interdisciplinary research work in the project.

In the first place, symptoms are defined as qualities of Global Change which appear to play a major role in the ongoing problematic developments both in the natural environment and in society.[3] The literature and political debates are full of these phenomena which synonymously might be called *trends* of Global Change [8,58]. We currently operate with about 80 symptoms including, e.g., the following:

- *Urban Sprawl*,
- *Increasing Significance of NGOs*,
- *Terrestrial Run-Off Changes*,
- *Accumulation of Waste*,
- *Increasing Mobility*,
- *Tropospheric Pollution*,
- *Increasing Consumption of Energy and Resources*,
- *Increasing Anthropogenic Greenhouse Effect*.

Currently, the catalogue of symptoms[4] is in a processing phase to formulate exact (semantic) definitions which then will be subjected to an iteratively repeated and updating expert-based review process to obtain a stringent basis for modelling.

The names of the symptoms have to be understood more as headlines than as conventional variable names. Names have been chosen in such a way as to characterize variations in time in order to underline the dynamic character of Global Change. Nevertheless, not only changes might be important but also the state or the "change of the change", i.e., the second derivative. Formally, if we assume for the moment that there is an underlying differentiable function, we have to indicate a symptom as a tupel $(X, \dot{X}, \ddot{X}, \ldots)$ where each component is not necessarily characterized by a number (compare section 4).

The temporal and spatial scales of symptoms vary from rather short-term and local phenomena, e.g., *Conversion* or *Degradation of Ecosystems* with scales of less than a month for small patches, via medium scales, e.g., the *Increase in Resource Productivity* determined by national policy with time scales of a few years, to rather long-term processes taking place on a global scale, e.g., *Global Climate Change*. These examples hint at the fact that each symptom probably has its own generic scale.

Many of the symptoms represent macro-phenomena with a variety of underlying micro-processes and events. To some extent this applies to trends of the natural sphere like *Loss of Biodiversity* [34] or *Contamination of Soils* [16] but equally in the anthroposphere, e.g., *Individualization* [4], *Increase of Aspirations* [52] or *Increase of International Disparities* [6]. We do not claim that it is needless or unnecessary to analyse these underlying constituents, yet we do not focus on these but rather on the macro-phenomena and how they are embedded into the overall context. This does neither exclude consideration of the respective actors who are operating within the symptom (or the interaction). This is of particuar importance when discussing options of global environmental management, which requires that the people involved are considered (see section 4).

Many of the symptoms might be indicated by quantitative measurable data like GDP, population or annual renewable freshwater resources and their rates of change. In some instances, however, they are rather related to qualitative data, e.g., literature surveys, expert knowledge, etc. As an example of such data, consider the "Global Assessment of Human Induced Soil Degradation" (GLASOD) which is based on expert evaluations of the state of soils using the FAO soil type map [38] as indicators for various symptoms concerning soil degradation. It is important to state that the necessity of qualitative data is not only due to insufficient statistics or measurement campaigns but rather a fundamental feature of Global Change: for example, *Emancipation of Women* includes such a variety of aspects that indicating

[3] In this sense, the catalogue of symptoms, iteratively to be improved by itself, hermeneutically ameliorates the initally vague notion of Global Change.

[4] Henceforth, symptoms from the catalogue are typesetted in *italic*.

it purely by data like "participation of woman with higher education" and/or "number of children per woman" [56] is far from sufficient. Other factors are equally important: for example, the role of woman within the respective culture and/or religion including, e.g., decision making on the number of children. We assume, however, that different states of a symptom are characterizable by vector-valued well-ordered variables which not necessarily have to be numbers but might be depicted by *linguistic* expressions as low, medium or high. The respective variables have to reflect the multiple character of the symptoms which, however, is context dependent (see the assessment of the intensity and the modelling attempts of the SAHEL SYNDROME below).

Global Change is not a homogeneous phenomenon but has a variety of regionally distinct facets. So far we have referred to symptoms of Global Change as abstract phenomena without regional explicitness. Now we consider symptoms as spatially dependent fields. According to the concept of natural scales for each symptom we have basic units for assessing their strength and/or direction. This type of scales is often implicitly used in other assessments of Global Change, e.g., the mixture between economic regions and a global $0.5^\circ \times 0.5^\circ$ gridcell coverage in the agriculture module of IMAGE2.0. Note, however, that the spatial resolution for assessing symptoms is often determined by the available data rather than the actual scale of functionality. In the geographically explicit analyses presented in this paper we assume homogeneousness across countries, e.g., for the number of people below the poverty line (compare section 3.2).

2.2. Basic vocabulary II: interactions

The particular vehemence of Global Change is not simply the result of symptoms occurring in parallel but is attributable to the closed *interrelation* between these phenomena. *Increasing Use of Energy and Resources* and *Installation of Large Scale Projects* (e.g., dams) are not two independent trends but closely related to each other. This interaction is, for example, of high importance within the ARAL SEA SYNDROME. The general interpretation of interaction suggests it may be specified by having a source (*Increasing Use of Energy and Resources*) and a target symptom (*Installation of Large Scale Projects*). Nevertheless some care has to be taken as it is not the increasing use of energy as such which brings about an installation of large scale projects. It is important to note that the mechanism of the interaction depends on a number of natural and/or socio-cultural conditions which, in the ideal case, are detectable – a major assumption for the assessment of dispositions of regions for certain syndromes (see below). In the example given, these conditions can be related to the general propensity for large scale solutions, i.e., largely enfavoured by the World Bank, the availability of adequate sites for erection of large dams, and sometimes questions of national identity [33,39].

In general, the conditions for interactions will be geographically dependent and we therefore can identify these *structural prerequisites* in spatial explicity. We refer to this concept as the *functional space* $\mathcal{F}$ of Global Change. Formally the functional space can be defined as a high-dimensional space spanned by axes given by typical indicators. As, however, some interactions might be conditioned by various conditions, each interaction is located in one or more subdomains within the space $\mathcal{F}$. Consider, say, the action from *Conversion of Ecosystems* on *Change of Surface Flows* [47]: on the one hand this action might occur under quite general circumstances on land, for example, simply by changing the infiltration depth of the soil. On the other hand, the generality of the trends does include this interaction to occur in rivers or streams, e.g., by changes of the river bank vegetation or the conversion of the river ecosystem itself.

Within the qualitative modelling approach any interaction is completely specified by its direction, its type, i.e., reinforcing or attenuating, and its connectivity, i.e., which components of the tupels of the contributing symptoms interact. We therefore introduce symbols which in the graphical representation used in the rest of this and related articles [7,23,51] encode the different aspects of the interactions. Table 1 summarizes these symbols. It has to be kept in mind, however, that though interactions between symptoms appear most relevant within Global Change, there might be other exogeneous determinants for one or the other symptom, e.g., natural catastrophes or political switches like the end of the socialism in Eastern Europe at the beginning of the 1990s.

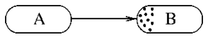
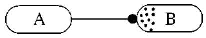
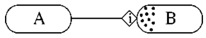
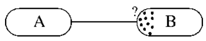
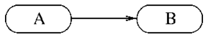
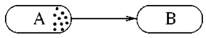
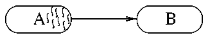
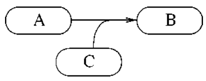
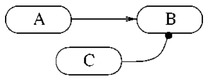
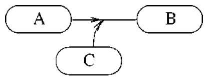
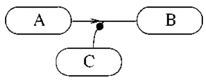
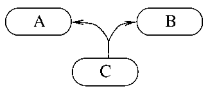
2.3. Basic vocabulary III: syndromes

Based on the syntax of symptoms and interactions defined in the preceding two subsections we might proceed by identifying all interactions which seem to be relevant for GC. As a matter of fact this *global network of interrelations* can be used as a powerful information tool and is pursued in an ongoing research project. In particular, this network would yield an impression of the overwhelming complexity of the problematique. The pure listing of possible interactions without further specification, however, limits the use of the network for policy support. Therefore a reduction of complexity is required where the functional properties of the system are adequately taken into account. This reduction can be motivated along three for the present independent lines, characterizable as follows:

1. By looking at the different interactions we observe that they do not occur wholly arbitrary. The interaction between *Impoverishment* and an *Extension/Intensification of Agriculture* on a low level is often, if not always, attended by a close interlinkage between *Impoverishment* and *Population Growth*. The reason is that both relations are similarly conditioned, i.e., they are located close together within the functional space $\mathcal{F}$. The

Table 1

Symbols to encode the basic types of interaction between symptoms used in networks of interrelations (see figures 1 and 2) [7,23,51]. In general, the arrowheads (→) indicate monotonous growth, the bulleted end of lines (–•) a monotonous decline. The dots and integrals within the ellipses designate action on the differentiated and integrated variable, respectively. The classes marked by an asterisk (*) are used in the present paper. For the sake of illustration it is assumed that the interaction can be represented by mathematical relations between the variables A, B, and C. Yet the monotony of the functions is the only information which will be used henceforth. Note that the overview is not complete as the more complex interactions (8)–(10) are depicted for the simple state–state interactions only. In principle, these types of interdependencies are possible for other components of the syndrome tupels as well.

Index	Differential equation	Monotony	Symbol	Remark
1*	$\dot{B} = f(A)$	$\frac{\partial f}{\partial A} > 0$		
2		$\frac{\partial f}{\partial A} < 0$		
3		non-monotonous		The index i hints at a remark in the text
4		unknown		The uncertainty might be due to expert disagreement and/or insufficient research
5*	$B = f(A)$	$\frac{\partial f}{\partial A} > 0$		Decreasing, non-monotonous or unknown functions are represented according to cases (2)–(4)
6	$B = f\left(\frac{\mathrm{d}A}{\mathrm{d}t}\right)$	$\frac{\partial f}{\partial(\mathrm{d}A/\mathrm{d}t)} > 0$		Correspondingly for $\dot{B} = f(\cdot)$
7*	$B = f(\int A\,\mathrm{d}t)$	$\frac{\partial f}{\partial(\int A\,\mathrm{d}t)} > 0$		Correspondingly for $\int B\,\mathrm{d}t = f(\cdot)$
8	$B = f(A) + g(C)$	$\frac{\partial f}{\partial A} > 0,\ \frac{\partial g}{\partial C} > 0$		For equal signs of partial derivatives; other monotonies according to (1)–(4); dependency on rate or integral is encoded as in (5)–(7)
		$\frac{\partial f}{\partial A} > 0,\ \frac{\partial g}{\partial C} < 0$		
9	$B = f(A, C)$	$\frac{\partial f}{\partial A} > 0,\ \frac{\partial f}{\partial C} > 0$		Other monotonies are encoded according to (2)–(4); nonlinear function $f(B, C)$; dependency on rate or integral is encoded as in (5)–(7)
		$\frac{\partial f}{\partial A} > 0,\ \frac{\partial f}{\partial C} < 0$		
10	$A = f(C)$, $B = g(C)$	$\frac{\partial f}{\partial C} > 0,\ \frac{\partial g}{\partial C} > 0$		Correspondingly for different dependencies and monotonies

common base of both interactions might be characterized by the failure of alternative means of income [12]. Within the syndrome concept it is claimed that the interactions appear mostly in clusters, called *syndromes of Global Change*. This is in clear contrast to more conventional modelling approaches where a single set of functional relationships is assumed which in some cases have regionalized, e.g., world economy models [32,37] or biome-based global vegetation models [19,42], in others just one single homogeneous parametrization [35,36]. It is important to underline that our spatial refinement is taking place in the *functional* and not in geographical space. This means that these patterns occur in a variety of regions all over the world. This is a more formal illustration of the syndrome idea.

2. A more semantic illustration starts from core problems of Global Change. Consider, say, the severe problem of world-wide soil degradation [16,41]. It is obvious that the causes and consequences of soil degradation are different between, say, the semi-arid Sahel region and Germany. Whereas in the first it is in particular the overuse of soils under difficult climatic conditions by poor farmers, in the North a variety of different, capital intensive, mechanisms is responsible for contamination, acidification, sealing, etc. On the other hand, the mechanisms found in the Sahel are similar to the ones in Afghanistan, Mongolia or even to the slash and burn cultivation in Amazonia. Correspondingly the processes of soil degradation happening in Germany are similar to those in other countries of the European Union or even to those of North America or Japan. In this way the global analysis of soil degradation leads to a decomposition of the processes at the civilization–nature interface into patterns – again called syndromes of Global Change.

3. Assume a far-reaching review of regional and/or case studies on environmental and social changes and/or processes is performed. In the first place, the review might not only make use of rigorous scientific investigations but also of the broader spectrum of soft knowl-

Table 2

Major patterns of civilization–nature interaction as identified in a first round of discussion between members of the project and of the German Advisory Council on Global Change (WBGU). These syndromes of Global Change are entitled by names either from prototypical regions or by catchwords for characteristic features. These patterns of non-sustainable development can be grouped according to basic human usage of nature: as a source for production, as a medium for socio-economic development, as a sink for civilizatory outputs. This list represents not a final result but rather a starting point for a thorough analysis potentially requiring iterative modification of classifications and/or characteristics.

	Utilization syndromes
SAHEL SYNDROME	Overuse of marginal land
OVEREXPLOITATION SYNDROME	Overexploitation of natural ecosystems
RURAL EXODUS SYNDROME	Degradation through abandonment of traditional agricultural practices
DUST BOWL SYNDROME	Non-sustainable agro-industrial use of soils and bodies of water
KATANGA SYNDROME	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
	Development syndromes
ARAL SEA SYNDROME	Damage of landscapes as a result of large-scale projects
GREEN REVOLUTION SYNDROME	Degradation through the transfer and introduction of inappropriate farming methods
ASIAN TIGER SYNDROME	Disregard for environmental standards in the course of rapid economic growth
FAVELA SYNDROME	Socio-ecological 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
	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

edge (experts, informal reports, etc.). The careful inspection of this knowledge base allows the observations to be grouped into typical frames.

Up to now, a mixture of these intuitive processes has been used in an extensive discussion process within the project, the German Advisory Council on Global Change and others to produce a first list of 16 syndromes of Global Change (see table 2). Within this initial step of syndrome analysis the patterns are characterized by (a) a name which either reflects the basic mechanisms or uses the name of a prototypical region, and (b) by a short description of the most relevant aspects and functional properties of the syndrome.

It is the final goal of syndrome analysis to tune the patterns against each other in order to obtain a consistent picture of Global Change. This requires checking whether the core problems of Global Change can actually be explained by these patterns and whether the conditions for the corresponding interactions indeed cluster within the functional space. In a nutshell, syndrome analysis is assessing the explanatory power of decomposing GC into syndromes. Syndromes of Global Change represent not only purely academic objects offering a very elegant analysis of GC, but they also constitute the basic management elements for global environmental policy. This is due to involving social actors and driving forces in a regional expliciteness and to the opportunity to analyse global environmental changes in the context of their respective causes and consequences.

3. Prototypical syndrome diagnosis: the SAHEL SYNDROME

So far we have discussed the concept of syndromes exclusively on an abstract level. Throughout the rest of the paper we want to illustrate its realization by using a single example, the SAHEL SYNDROME.

3.1. The SAHEL SYNDROME

The key characteristic of the SAHEL SYNDROME is described as the use of agriculturally marginal land by a poor rural population living in a context offering few or no alternative means of livelihood – thus leading to an ever increasing degradation of their environment. This syndrome typically occurs in countries at a low level of socio-economic development and in regions that are vulnerable to human impacts because of their relatively weak agricultural production potential. This production potential can either be limited as a result of aridity or temperature constraints or due to insufficient soil-fertility conditions. The main driving forces and effects are inherent in all forms of the SAHEL SYNDROME, regardless of the types of production limitations given by natural environmental conditions. This enhances the explanatory force of the model and ameliorates its applicability to different regions – including poverty-driven agricultural overuse practices in areas usually not associated with the term "Sahel", such as the Amazonian basin or the rainforest areas of some African countries.

It is obvious that the different mechanisms summarized in figure 1 act on different time scales and in different

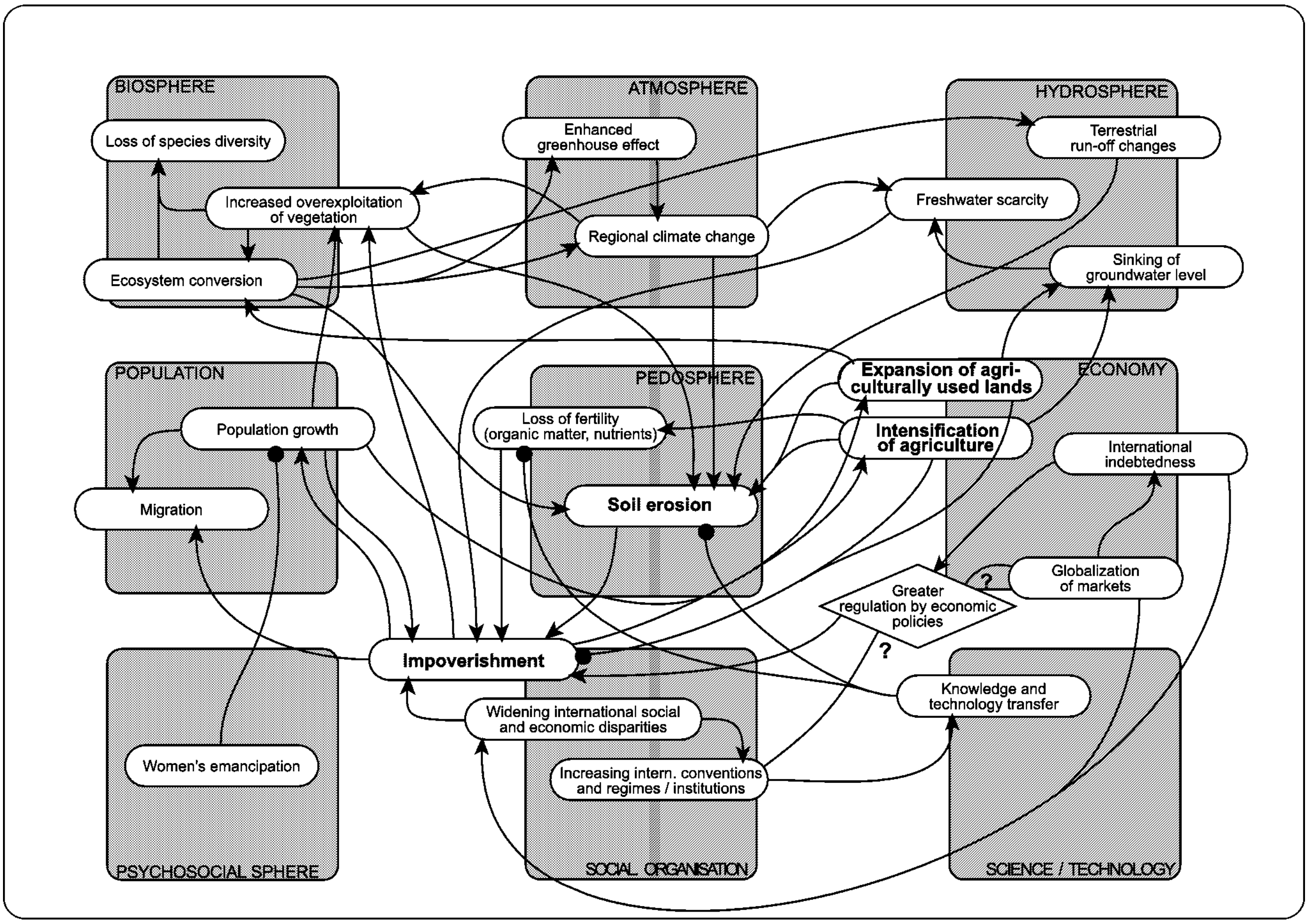


Figure 1. SAHEL SYNDROME specific network of interrelations. This network describes the complex interactions between symptoms of different Earth System spheres that make up the typical pattern of overuse of agriculturally marginal land. The core symptoms, denoted by the shaded ellipses, outline the vicious circle of the syndrome and are constituents for the syndrome. Here the refined encoding of the interactions as defined in table 1 has been neglected for the sake of readability. For a detailed depiction of the core of the syndrome see figure 2.

strength. Yet the wiring diagram shows that there are basically two closed loops: the first involves the direct loss of resource quality, e.g., *Soil erosion* or *Increased overexploitation of vegetation*, and its re-enforcing feedback onto an increased impoverishment. The second loop entails a Regional Climate Change and is thus operating on much larger time scales. Therefore, if we concentrate on short to intermediate time-scales (5–10 years) the first loop can be considered as the major flying wheel of the syndrome.

More specifically, this core mechanism or kernel consists of a vicious circle, relating the trends *Impoverishment*, *Intensification/Expansion of Agriculture* and *Soil Erosion* – the latter leading to productivity losses and subsequently increasing poverty. The circle competes with the direct income effects – in terms of basic goods for life support – from agricultural activities which to some extent can counteract *Impoverishment*. This core mechanism of the syndrome constitutes its basic dynamic behaviour and is depicted in figure 1 by the shaded ellipses. Case studies of peasant agro-ecosystems in poor countries show that this basic mechanism describes the situation of many people in the "Third World", caught in a typical socio-ecological trap (see, e.g., [27,45] and references therein). In figure 1 we have neglected to specify the type of connectivity of the interactions and instead included the essential mechanisms surrounding the kernel. This includes political and economic settings which are often characterized as inappropriate for the rural population, e.g., unfavourable terms of trade enforcing cultivation of cash crops on productive sites or unbalanced focuses on urban development. Other factors include insufficient security of land use rights and/or a general pressure on ethnical minorities.

The refined core mechanism is shown in figure 2 where the types of interactions are specified as introduced in table 1. The basic assumption is that it is the absolute level of poverty which drives the rural population to extend agriculture and thus an "integral part of impoverishment" acts towards the intensification/extension of agriculture, jointly entitled by the notion "agricultural activity". For the sake of illustration we therefore have introduced the name "poverty" for this integrated part of the trend *Impoverishment*. Moreover, on marginal sites it is the absolute degree of intensity which enforces soil degradation. Within the current description we do not further specify the "minimal" degree of intensity leading to soil erosion – a refinement to be introduced below. Finally, we assume

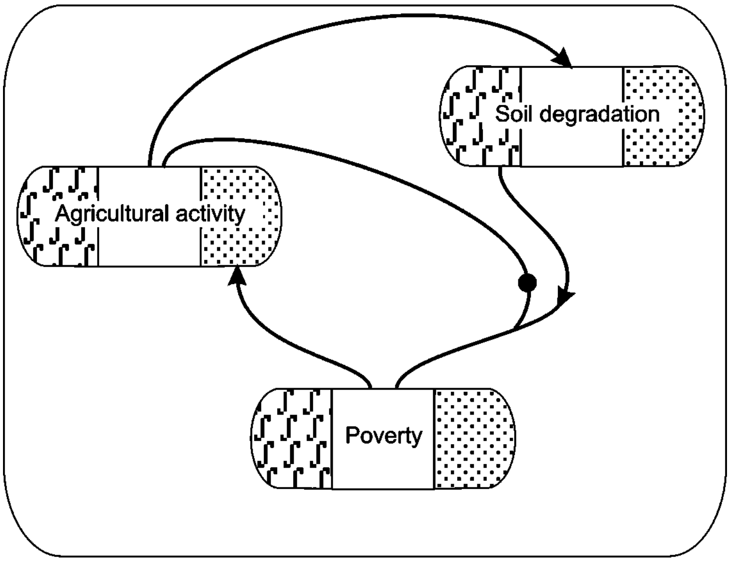


Figure 2. The central mechanism (core) of the SAHEL SYNDROME with interactions specified according to table 1.

that poverty is a function of the fertility of the soil and of the level of agricultural activity.

3.2. Concepts of syndrome diagnosis

It is a major task of syndrome diagnosis to detect geographical patchworks which sufficiently characterize syndromes on the global scale. The analysis has to be detailed enough to get a reasonable overview on the entire dynamics of Global Change and it has to be coarse-grained enough to avoid getting lost in details and accidentals. Syndrome diagnosis runs along three lines which are independent in the first place, but are required to be mutually consistent (see below): syndrome *disposition*, *exposition*, and *intensity* (for more details on the concepts see [51]). We explain the concepts by their direct implementation for the analysis of the SAHEL SYNDROME.

Disposition. In a nutshell, disposition is the inverse of what in medical science is known as immunity. In order to analyse whether a region is prone to the specific mechanisms of the SAHEL SYNDROME, it has to be asked which determinants force the rural population to use their marginal natural environment for a significant portion of their income. We decompose the investigation into two, analytically independent parts: (a) a natural component which evaluates the natural environment with respect to "marginality", and (b) a socio-economic component which investigates the different means of income – more appropriately entitled life support – for the population in the respective region. This differentiation is not for all syndromes as clear cut as it is here, in most cases the natural, economic and socio-cultural aspects are more intriguingly interrelated.

Factors determining the marginality of a region with respect to natural productivity include climate, soil properties, surface water availability and hillyness. Within our analysis these factors have been combined in the form of a *logical evaluation tree* which is computed by use of fuzzy logic [9,63]. This type of fuzzy analysis is appropriate for combining information of structurally different types, e.g., qualitative vs. quantitative data, with variant degrees of certainty for the data itself and the type of systematic interrelations.

The natural component of the disposition [9] is assessed using information on the regional climate (monthly mean temperature, sum of precipitation, cloudiness), soil-fertility [26,64], and slope. The socio-economic component of the disposition requires to assess the degree of subsistence and small-scale farming in a country which is hardly assessed within a single variable. We have therefore used data on the fraction of labour force in the agricultural sector to determine the degree of alternative means of income for the rural population. The importance of subsistence farming is evaluated using the deficit in the coverage of calory needs, if only food supply as indicated by the data for marketed foodstuffs is considered. The entire analysis of the disposition for the SAHEL SYNDROME is the subject of another paper in this volume [30].

The determinants of the disposition are persistent over rather long periods and they are considered to be only slightly modified by the dynamics of the syndromes. This allows us to consider the disposition as an *early warning indicator*: as regions with a high disposition are endangered with respect to syndromatic environmental degradation, it has to be a major goal of environmental policy to reduce disposition in the long term. For the SAHEL SYNDROME this would require reduction of the extent to which the rural population is dependent on marginal natural resources and/or that major climate changes responsible for marginality in previously stable regions were prevented.

Intensity. Whereas disposition determines whether a syndrome might *become* active, *intensity* measures whether it actually *is* active in a certain region. Therefore it has to be examined whether the contributing symptoms show up because of the proposed mechanisms. It is most direct to formalize the mechanism in terms of a simple mathematical model and to obtain conditions for the temporal behaviour of the symptoms from this model. Without loss of generality we can formalize the central vicious circle of the SAHEL SYNDROME by writing

$$\frac{\mathrm{d}A}{\mathrm{d}t} = f_1(P), \tag{1a}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = f_2(A), \tag{1b}$$

$$P = f_3(A,S), \tag{1c}$$

with $A(t)$ standing for the level of agricultural activity, $S(t)$ for the productivity of the soil and $P(t)$ for poverty as functions of time. The monotony properties as they are indicated in figure 2 are reflected by

$$\frac{\partial f_1}{\partial P} > 0, \tag{2a}$$

$$\frac{\partial f_2}{\partial A} > 0, \tag{2b}$$

$$\frac{\partial f_3}{\partial S} > 0, \qquad \frac{\partial f_3}{\partial A} < 0. \tag{2c}$$

In order to proceed we have to further specify the functions f_i. For the sake of simplicity and due to data limitations (see below) we assume f_i to be linear.[5] Moreover, by inserting equation (1c) into equation (1a) we can eliminate P from the system and obtain

$$\frac{\mathrm{d}A}{\mathrm{d}t} = f_1\big(f_3(A,S)\big) = g(A,S) = g_1 A + g_2 S + g_3, \tag{3a}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = c_1 A + c_2, \tag{3b}$$

where $g_1 < 0$, $g_2 > 0$, $c_1 > 0$ and c_2, c_3 undetermined. Simple and straightforward integration yields

$$A(t) = K_0\,\mathrm{e}^{\alpha_+ t} + K_1\,\mathrm{e}^{\alpha_- t} - \frac{c_2}{c_1} \overset{t\gg 0}{\approx} K_0\,\mathrm{e}^{\alpha_+ t}, \tag{4a}$$

$$S(t) = \frac{K_0 c_1}{\alpha_+}\,\mathrm{e}^{\alpha_+ t} + \frac{K_1 c_1}{\alpha_-}\,\mathrm{e}^{\alpha_- t} + K_2 \overset{t\gg 0}{\approx} \frac{K_0 c_1}{\alpha_+}\,\mathrm{e}^{\alpha_+ t}, \tag{4b}$$

where the constants K_i are determined by the initial conditions and $\alpha_\pm = (g_1 \pm \sqrt{g_1^2 + 4g_2c_1})/2$. As, however, we neither know the initial conditions nor the parameters g_i and c_i we cannot check the validity of the system by comparing it with measured data directly. Yet for $t \gg 0$ we easily obtain from equations (1c), (4a), and (4b):

$$\frac{\mathrm{d}A/\mathrm{d}t}{A} = \frac{\mathrm{d}S/\mathrm{d}t}{S} = \frac{\mathrm{d}P/\mathrm{d}t}{P} = \text{const} = \alpha_+. \tag{5}$$

This means that the specification of the proposed mechanism by equations (1a)–(1c) and its linear realization requires the relative temporal changes to follow equation (5), i.e., they are (a) equal and (b) constant in time.

To check whether condition (a) is fulfilled one needs at least data for (S,A,P) at two distinct times (t_1,t_2) to calculate the time derivative numerically, while for condition (b) at least three times would be necessary. The latter requirement exceeds the present global data availability. As a measure for poverty in the range of the subsistence level (P) we used the head count index which gives the number of people with an income below a poverty line defined by basic needs with respect to nutrition and non-food consumption (for the difficulties in defining such basic needs see [44]). We had to rely on the data collection of [57] which provides country-wide rural poverty head-count indices for the '80s and for the year 1992 and on the data set of [20] covering the same times. Both data sets concentrate on developing countries. For 96 countries with available data we calculated the mean relative change $(\mathrm{d}P/\mathrm{d}t)P$ for the time interval from 1985 to 1992.

In the case of the soil degradation data we used the GLASOD database [38], which besides others contains information about the severity of anthropogenic soil degradation (state of soil degradation S) and the present rate of anthropogenic soil degradation ($\mathrm{d}S/\mathrm{d}t$). The data was collected during the 1980s and is therefore commensurable with the poverty data sets. The spatial units of the data set are the polygons of the FAO soil-type map which usually implies a sub-country resolution. To obtain the relative change of soil degradation, the estimated rate from the GLASOD data set had to be scaled to the unit of severity by a factor which we obtained from comparisons with estimations reported in [41]. We developed subsequently a combined measure for the intensity and the extent of agricultural use A in a country based on the indicators livestock and arable land. With respect to the livestock we considered the number of camels, cattle, sheep and goats. To make these numbers comparable, they were weighted according to the livestock unit [25]. To include the arable land in the measure we compared the mean production of one livestock unit (meat, milk) with the mean millet yield of one hectare [14] in terms of energy content. Using the data sets (country-wide) of [62] we calculated the mean relative change in agricultural intensity and extent $(\mathrm{d}A/\mathrm{d}t)/A$ for the time interval from 1985 to 1992.

On the basis of these data we define the intensity of the SAHEL SYNDROME at location $\mathbf{r}$ as

$$I_{\mathrm{S}}(\mathbf{r}) = \frac{[\max_{\mathbf{r}} T(\mathbf{r})] - T(\mathbf{r})}{\max_{\mathbf{r}} T(\mathbf{r})} \tag{6}$$

[5] We remark that this assumption is reasonable for some finite initial interval only. It is obvious that we have $\mathrm{d}S/\mathrm{d}t \overset{S\gg 0}{\longrightarrow} 0$ due to the finiteness of the soil resources.

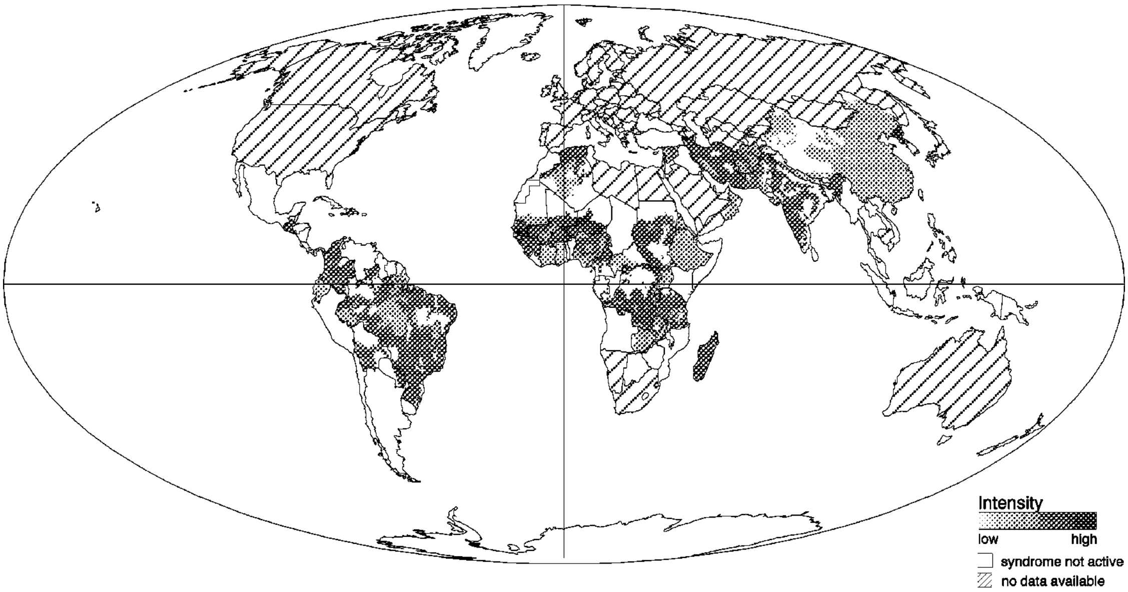


Figure 3. Intensity of the SAHEL SYNDROME as it is given by equation (6). In the dark shaded regions the vicious circle between impoverishment and soil degradation is detected to having been active in the late ’80s and early ’90s.

with the spatially dependent variable

$$T(\mathbf{r}) = \left|\frac{\mathrm{d}A/\mathrm{d}t}{A} - \frac{\mathrm{d}S/\mathrm{d}t}{S}\right| + \left|\frac{\mathrm{d}S/\mathrm{d}t}{S} - \frac{\mathrm{d}P/\mathrm{d}t}{P}\right| + \left|\frac{\mathrm{d}P/\mathrm{d}t}{P} - \frac{\mathrm{d}A/\mathrm{d}t}{A}\right|. \quad (7)$$

Now the variables A, S, and P are no longer abstract entitities but given by the real data instead. Thus a value $T(\mathbf{r}) = 0$ indicates that these data fulfill the necessary condition (5) derived from the formalisation of the core mechanism. This gives a strong hint at the activity of the vicious cycle. The intensity $I_\mathrm{S}(\mathbf{r})$ varies between zero (no intensity) and one (highly intensive). The global distribution of the intensity I_S is depicted in figure 3. The general distribution corresponds well with the “educated guess” assessment: besides the name-giving region and its sorroundings of the West African Sahel itself, the syndrome is diagnosed in wide parts of Brazil, Columbia, South Asia, in particular the (semi-)arid regions of Afganisthan, Pakistan and India, and Mongolia. Counter intuitive intensities within some regions, e.g., high values in North Korea or low intensity in the Chad, can mainly be related to deficiencies and/or inconsistencies in the data sets.

The necessary use of global datasets for this kind of analysis generates a number of difficulties when interpreting or applying these global measures. Though being elegant in principle, the utilization of time series is hindered by limited data availability and compatibility. Therefore it is important that these global assessments are complemented by regional information, i.e., case studies scrutinizing local processes [40].

The methodolgy to measure the intensity of the SAHEL SYNDROME sketched in the previous paragraphs is an almost ideal one as we have some kind of a time series for the data needed. In most of the other cases investigated so far (see, e.g., [18,23,51]) either no indicators for the relevant symptoms or no time series are available. In these instances other, more indirect algorithms have to be employed.

Exposition. A region which is prone towards a specific syndrome, i.e., has a *high disposition*, is not necessarily affected by the syndrome, i.e., it might have a *low intensity*. This is due to the fact that though the structural prerequisites for the interactions within the syndrome are given, the symptoms have not been “initialized” in such a way that the mechanism starts running. The factors initializing the syndrome in this way are called *exposition*. These events can be either elements of our approach, e.g., other syndromes either as a whole or in parts, or external to our analyis, e.g., droughts, floods, volcanic eruptions, earth-quakes, etc. The factors can be natural in origin as well as anthropogenic to various degrees, e.g., wars or political changes as the end of the socialism in Eastern Europe in the early 1990s or the end of colonialism in the late ’40s and ’50s.

If we consider the SAHEL SYNDROME again quite a number of aspects can be listed which might prevent, or at least delay, the rural population from becoming involved in the vicious circle: appropriate cultivation techniques, low population to be supported by the natural resources, “good” climatic years with sufficient agricultural productivity, etc. On the other hand a number of factors can be made responsible for the lift off of the vicious circle: droughts for months or even years as occurred in the Sahel region in the 1960s, or in contrast floods leading to losses of terraces which form an appropriate cultivation technique on steep slopes, international economic events like drastic changes of the terms of trades or even of local prices, and many others [51]. Which of these or other factors actually served as exposition factors or events in which region identified as affected by the SAHEL SYNDROME is still an open question and has to be investigated in detail in the near future.

The main difference between exposition factors triggering the spread of a syndrome and the elements of the disposition is the time scale: whereas disposition is persistent on long time scales exposition factors are considered to take place on much shorter time scales. Moreover, exposition involves much more stochasticity and is therefore much harder (a) to forecast and (b) to control. Thus, though representing a policy option in principle, the avoidance of exposition factors is only second best to the more robust reduction of the disposition.

As has been mentioned before, the three concepts just introduced have to be assessed consistently. Logically, consistency implies the conjunction of disposition and exposition to be a sufficient and necessary condition for intensity. Based on this a total check of the measurements with respect to internal compatability is possible. So far we have carried out a check for disposition and intensity of the SAHEL SYNDROME which has shown a rather low degree of inconsistency [31], i.e., there are only a few regions with significant intensity which have not been detected to be disposed to the syndrome.

4. Syndrome modelling: qualitative differential equations

The concepts of syndrome diagnosis and first results discussed so far concentrate on a systematic assessment of the current processes of Global Change. Yet it is the intricate dynamics of these processes which might bring about the major impacts of GC on human society. Thus, at least weak projections of the main lines of development of globally relevant interactions between civilization and nature are required. Moreover, the complexity of GC requires systematic evaluations of the dynamic implications of any kind of policy action: originally intended effects might be accompanied by significant, possibly devastating, side-effects or might even turn into catastrophes themselves. Syndromes of Global Change are per se dynamic patterns changing in the course of time but in order to forecast their behaviour more specifically and to allow the indicated type of policy evaluation, some kind of computerized models are needed.

4.1. Quantitative versus qualitative modelling

Within a conventional approach a model for the dynamics of a syndrome would be based on ordinary differential equations like the ones used for the intensity assessment in section 3.2. Though obvious at a glance, it is by no means trivial that this formulation is feasible as the following questions have to be answered in the first place:

1. Is it adequate to characterize the relevant elements of the system by differentiable mathematical functions? What do these variables look like and how are they related to measurable quantities? This set of questions seems to be easy to answer for, say, the net primary productivity of an ecosystem but is much more debatable for social disparities, the spreading of western consumption and lifestyles or biological diversity.
2. Is it appropriate to use exact mathematical functions to mutually relate the different variables involved? What is the basis for these functions, e.g., statistical regressions, first principles, etc., and what do these functions look like? Is uncertainty included? Again the answers appear to be obvious for some modelling attempts, e.g., global circulation models where the usage of Navier–Stokes equations is founded on general hydrodynamics. On the other hand, the suitability of such functions for describing social or highly complex biological systems is much more doubtful – not alone for data or knowledge reasons but in principle.

It is obvious that in the transdisciplinary attempt to model Global Change these questions play a major role though they cannot be answered rigorously. Within conventional modelling approaches they are often treated pragmatically by using measured indicators as variables and parametrized functions to relate these. Successive fitting procedures are then applied to reproduce the past – at least as it is represented in the data. Besides the fact that the extent of the model is limited by the availability of data, there remains significant doubt as to the generalizability: even if the model is "good" for the data range covered so far, the authenticity in unexperienced regimes remains open. This is especially true for pure regression models without any functional input or reduced form models as often used in integrated assessment models of climate change [59].

The modelling method which we employ for a soft projection of the dynamics of syndromes rests on a few rather weak assumptions:

1. We presume the existence of continuous mathematical functions to characterize the time evolution of the important elements of the system. Yet it is *not necessary* to specify the variables more rigorously, e.g., in terms of measurable data. The qualitative variables to be used henceforth are only assumed to be well-ordered by the so-called *landmark values*.
2. Concerning the functional relationships between the variables, the qualitative modelling approach rests on similar assumptions: only their existence is assumed; the actual forms, however, have to be specified only in terms of monotony and corresponding landmark values. We thus consider entire *classes* of ordinary differential equations.

These general assumptions allow us to implement the calculus of *Qualitative Differential Equations* (QDEs) [24] as the basic modelling concept for the dynamics of syndromes. The extension of the classical modelling concept to qualitative relationships improves the ability to model important components of GC for which only qualitative knowledge exists, e.g., the increase of aspirations, the spreading of western lifestyles, or, as an example from the natural sciences, biodiversity. This gain is to some extent compensated by the limited concreteness of the results: instead of a single future the QDE approach computes *all* solutions of *all* ordinary differential equations in the class specified in the model. The purpose of this paper is to illustrate the concept and its applicability for analysing Global Change. Though producing some interesting results, it is obvious, however, that its full power has to be assessed in a more extensive modelling exercise.

As we have done for the concepts of syndrome diagnosis we want to demonstrate the basic ideas of the modelling approach by its application to the core of the SAHEL SYNDROME. Though rather simple, the scheme implemented can illustrate both the major features and the possible use of the QDE method for evaluating options of global environmental policy.

4.2. The qualitative dynamics of the SAHEL SYNDROME

We start from the central mechanism of the syndrome as it is depicted in figure 2. Henceforth we consider the symptoms involved in the core as qualitative variables which are characterized in terms of *quantity spaces* (for detailed definitions of the various concepts and their mathematical foundation see [24]). A quantity space is defined as a well-ordered set of symbols, the so-called *landmark values* l_j which are symbolic names representing specific values of the underlying function. For analytic reasons and for the sake of simplicity we use "degree of soil degraded" (with respect to some fictitious natural reference) or simply soil as the variable for the symptom "soil degradation". We employ the quantity spaces

$$\begin{aligned} &\mathsf{Agr}: && 0 < ms < total, \\ &\mathsf{Soil}: && 0 < out, \\ &\mathsf{Pov}: && 0 < ex < out, \\ &\mathsf{Yield}: && 0 < out, \end{aligned} \tag{8}$$

where *out* denotes the maximal possible value for which the model is considered to be valid. Here Agr stands for the level of agricultural activity, Soil for the degree of soil degraded, and Pov for the poverty level. Furthermore, we have introduced the agricultural Yield as an auxiliary variable. The maximal sustainable agricultural activity is demarcated by *ms*, its maximal possible level by *total*. Concerning poverty the landmark value *ex* is used to indicate massive and existential poverty, above which attainment of much beyond the minimal necessities is precluded [27]. The value *out* in this context basically might be identified with losses of life, but could equally be interpreted as synonymous for the onset of significant outmigration.

It is an important property of any model formulated by qualitative differential equations that the limits of the applicability of the model are encoded by the minimal and maximal landmark values of each variable. Thus if such a limit is achieved, e.g., indicated by the value "*out*" for poverty in equation (8), the real world correspondent is assumed to "leave the model". In the context of syndrome modelling this might imply (a) simply a disappearance of the syndrome, (b) an ecological or socio-economic "fatal" outcome for the region (like for the Aral Sea), or (c) the succession or enforcement of other syndrome(s), e.g., the strengthening of the FAVELA SYNDROME by migration of "Sahel peasants" into the cities.

We can now describe the value of the underlying functions using landmark values and intervals. We specify the qualitative value by a qualitative magnitude *qmag* and the direction of change of the underlying function, indicated by *qdir*. Formally we write $X = \langle qmag, qdir \rangle$ which, in terms of the underlying function $f_X(t)$, is given by

$$qmag = \begin{cases} l_j^X & \text{if } f_X(t) = l_j^X, \\ (l_j^X, l_{j+1}^X) & \text{if } f_X(t) \in (l_j^X, l_{j+1}^X), \end{cases} \tag{9}$$

and

$$qdir = \begin{cases} \uparrow & \text{if } \dot{f}_X(t) > 0, \\ \circ & \text{if } \dot{f}_X(t) = 0, \\ \downarrow & \text{if } \dot{f}_X(t) < 0, \\ \updownarrow & \text{if unknown.} \end{cases} \tag{10}$$

We also characterize the derivatives by appropriate landmark values, which facilitates the formulation of the entire model. We thus write

$$\begin{aligned} &\frac{\mathrm{d}}{\mathrm{d}t}\mathsf{Agr}: && mout < 0 < out, \\ &\frac{\mathrm{d}}{\mathrm{d}t}\mathsf{Soil}: && mout < 0 < out, \end{aligned} \tag{11}$$

where *mout* denotes the negative limits of the model (see above) and $(\mathrm{d}/\mathrm{d}t)\mathsf{X}$ denotes the quantity space for the function $\dot{f}_X(t)$. Moreover, we have neglected the specification for $(\mathrm{d}/\mathrm{d}t)\mathsf{Pov}$ as it is only poverty itself which will be needed henceforth. Note that we allow both directions, i.e., we include soil regeneration processes.

The time evolution of a function $f_X(t)$ is given as a sequence of qualitative values, e.g., $\mathsf{Pov}(t)$: $\langle(0, ex), \uparrow\rangle, \ldots, \langle ex, \uparrow\rangle, \ldots, \langle(ex, out), \uparrow\rangle$. This characterization of the function $f_X(t)$ has a number of important implications. Time itself is now a qualitative variable, i.e., it is no longer quantitatively specified as years or seconds, but is only indirectly given as a well-ordered set in terms of landmarks, i.e., $t_j = f_X^{-1}(t)|_{f_X(t)=l_k}$ for some variable X and related landmark l_k^X, and in terms of open intervals, i.e., (t_j, t_{j+1}). Consequently, we cannot specify, say, the number of people below the poverty line at a certain point in time. Yet for $\mathsf{Pov} = \langle ex, \uparrow\rangle$ we know that there is increasing existential poverty at a distinguished point in time. Further, we do not rigorously define what we mean for poverty. There is a long ongoing debate on how poverty can be quantitatively assessed, e.g., whether it has to be measured by the mean GDP of a country, by the number of people with an income below a certain threshold or by assessing the Gini coefficient [44]. We do not rely on one or the other of these quantifications. It is obvious that our type of characterization is not very useful while it is not embedded in an extended context. This asks for the drivers and consequences of poverty beyond the existential level – a question which brings us back to the interactions at the core of the SAHEL SYNDROME. The basic idea of representing interactions within the methodology of qualitative differential equations is to introduce various qualitative *constraints* for the functions $f_X(t)$ which can be checked for qualitative behaviour. The most basic constraint concerns *corresponding values* between landmarks of different quantity spaces, expressed by $cv_{jk}(X, Y) \equiv (l_j^X, l_k^Y)$ for two qualitative variables X and Y which implies $f_X(t) = l_j^X$ if and only if $f_Y(t) = l_k^Y$. Further we will make use of monotony constraints which in their simplest form are written as

$$Y = M_{\pm}(X) \tag{12}$$

with the plus (minus) sign subscript for $\partial f_Y(x;t)/\partial x > 0$ ($\partial f_Y(x;t)/\partial x < 0$). If it is possible to assign corresponding values cv_{jk} between X and Y we shortly write

$$Y = M_{\pm}\big(X; cv_{jk}^1(Y, X), \ldots, cv_{lm}^i(Y, X)\big). \tag{13}$$

Finally, we make use of the qualitative analogue of multiplication which is written as $Z = \mathit{mult}(X, Y)$ for functional relations $f_Z(t) \equiv f_X(t) \cdot f_Y(t)$. Using these notions we express the interactions depicted in figure 2 by

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathsf{Agr} = M_+\big(\mathsf{Pov}; (0, \mathit{ex})\big), \tag{14a}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathsf{Soil} = M_+\big(\mathsf{Agr}; (\mathit{mout}, 0)(0, \mathit{ms})(\mathit{out}, \mathit{total})\big), \tag{14b}$$

$$\mathsf{Yield} = \mathit{mult}\big(M_-\big(\mathsf{Soil}; (0, \mathit{out}), (\mathit{out}, 0)\big), \mathsf{Agr}\big), \tag{14c}$$

$$\mathsf{Pov} = M_-(\mathsf{Yield}). \tag{14d}$$

Equation (14a), for example, can be read as: the change in agricultural activity is a monotously increasing function of the poverty, whereby the change is positive as soon as poverty exceeds the existential level "*ex*".

Equations (14a)–(14d) completely specify the qualitative model of the core of the SAHEL SYNDROME henceforth investigated in more detail (compare equations (1) for the quantitative analogue of the qualitative model). The most significant extension of the "pure" core mechanism as graphically represented in figure 2, is the multiplicative constraint for agricultural yield. This has been introduced to express that the yield is considered to be zero if the agricultural activity is zero and, inversely, that the model is assumed to be left by $\mathsf{Soil} = \langle \mathit{out}, \uparrow \rangle$ if the soil degradation precludes any income from agricultural activity. This type of behavior cannot be expressed by a simple monotony constraint.

Initial conditions have to be set in terms of consistent qualitative values, i.e., they have to be compatible with the constraints. Yet it is not necessary to specify all independent values for *qmag* and *qdir*, but the calculus allows computation of the set of all consistent initial conditions. If we would be interested in the prediction of the model for a specific region starting from a specific time, we would need to choose the corresponding initial condition. Yet here we intend to investigate the entire set of possible evolutions of the syndrome. Therefore we henceforth concentrate on situations which start with either increasing agricultural activity, i.e., $(\mathrm{d}/\mathrm{d}t)\mathsf{Agr} = \langle (0, \mathit{out}), \cdot \rangle$ or ongoing soil degradation, i.e., $(\mathrm{d}/\mathrm{d}t)\mathsf{Soil} = \langle (0, \mathit{out}), \cdot \rangle$. Here the dot $(\cdot)$ stands synonym for "for the current argument it does not matter what *qdir* is". According to equations (8) and (14) this implies restricting the initial conditions by at least one of the two possibilities

$$\mathsf{Agr} = \big\langle (\mathit{ms}, \mathit{tot}), \cdot \big\rangle, \tag{15a}$$

$$\mathsf{Pov} = \big\langle (\mathit{ex}, \mathit{out}), \cdot \big\rangle. \tag{15b}$$

Here we have excluded $\mathsf{Agr} = \langle \mathit{tot}, \cdot \rangle$ as this would imply $(\mathrm{d}/\mathrm{d}t)\mathsf{Soil} = \langle \mathit{out}, \cdot \rangle$, i.e., the model starts at its own limit which we would like to exclude. The same applies for $\mathsf{Pov} = \langle out, \cdot \rangle$ which is therefore cancelled, too. Note that the two restrictions (15) do not completely determine the initial qualitative values of all variables. Thus there is a larger number of possible initial states which have to be investigated. To simplify the representation of the results, we introduce the *qualitative state of the system* at time t by $QS[t] \equiv [\mathsf{Agr}(t), \mathsf{Soil}(t), \mathsf{Pov}(t)]$. Correspondingly, we call the time evolution of $QS[t]$ the *qualitative behaviour of the system*. In order to compute the *set of possible behaviours*, we have made use of the simulation software package QSIM distributed by the University of Texas at Austin. Starting from a specification of the initial condition like equation (15), the system finds all consistent initial conditions and is able to identify all types of qualitative behaviours of the system which are compatible with the constraints. Figure 4 shows the entire "tree of development" of the system. Each box represents a possible qualitative state of the system at a certain qualitative time, i.e., either a specific point in time corresponding to a landmark value of one or more underlying functions or a time *interval* between two consecutive points. It might be the case, however, that a specific point in time is equal to infinity, preventing its own achievement as that of consecutive qualitative states. At each time point a branching can occur between different solutions, depending on the functions reaching a landmark value. This implies that, though equally notated, the times for the distinct qualitative states are not comparable across different branches and leaves of the tree. The two initial conditions at the left-hand end are characterized either by a level of agricultural activity above the maximally sustainable level *ms*, or by a poverty level beyond the existential landmark *ex*. At the other three possible starting points, indicated by the asterisks, both qualitative variables are increased. If we pick up the idea of exposition as a triggering factor for the syndromes dynamics, two classes of such events might induce one or the other initial condition from a previously sustainable state, i.e., agriculture below *ms* and poverty below *ex*:

- Social events can lead to a "non-poverty" driven rise of agricultural activity exceeding the maximal sustainable level (I_2) or, correspondingly, might provoke rapid impoverishment (I_1). Examples include population growth, increased demand for market products, the introduction of new technologies, and the displacement of local authorities by national governments [55].
- Equally, or additionally, natural events might induce a *decrease* of the maximally sustainable level of agriculture, i.e., the same type and intensity of agricultural production might become unsustainable due to, for example, floods (significant loss of soils due to water erosion, damage to cultivation practices like terraces, etc.) and droughts (high wind erosion, deterioration of natural growth conditions [9], etc.).

From figure 4 it can be seen that there are essentially five classes of solutions, marked by the numbers and grouped according to the basic characteristic of the final state. The actual achievement of one or the other solution or solution class depends on the one hand on the actual form of the underlying functions which, as repeatedly has to be underlined, may not be exactly identifiable, and on the other hand on the initial condition. The concept of the functional space $\mathcal{F}$ introduced in section 2.2 implies that the functional form depends on various natural and social conditions which therefore influence the outcome of the model. Here we qualitatively discuss these factors for the five solution classes of the model characterizable as follows (the numbers in the list refer to those in figure 4):

(1) Solutions with soils that regenerate completely, since there is only very moderate agricultural activity. Note that this class can be realized for only one initial condition, namely $QS[t_0] = [\langle(0, ms), \uparrow\rangle, \langle(0, out), \downarrow\rangle, \langle(ex, out), \downarrow\rangle]$. From the relatively long time scale for soil regeneration, it can be expected that the end points of the time evolution within the model are achievable for very long times only, i.e., decades to centuries. Further, it is necessary that, in spite of the long time scale involved, agriculture never exceeds the maximal sustainable level and poverty stays below the existential landmark *ex*. Together this implies that this solution would hardly be detected if searched for in the real world.

(2) Stationary solutions achieving an equilibrium between poverty and agricultural activity. This equilibrium holds for all times as each derivative is equal to zero. Here, people are using the natural resources just at the sustainable level, which inversely is sufficient to sustain the livelihood on a satisfactory level. This solution requires a good balance between natural resources and socio-economic conditions which, however, cannot further be characterized with the constraints used so far. It is observed that the stationary solution with a highly degraded soil ($\mathsf{Soil} = \langle out, \circ\rangle$) is possible for the initial condition with increased agriculture only, the solution with a slightly degraded soil for the starting constellation with raised poverty solely.

(3) Solutions with rapid soil degradation where the initialized increase of agricultural activity leads to a "complete" degradation of soils with a total loss of productivity. This class of solutions is feasible for the initial condition with elevated agricultural activity only, i.e., $QS[t_0] = [\langle(ms, tot), \downarrow\rangle, \langle(0, out), \uparrow\rangle, \langle(0, ex), \uparrow\rangle]$. The feedback of soil degradation does not lead to an increase of impoverishment beyond the existential level which implies that the people have some alternative means of income.

(4) Outcomes leaving the syndrome model on the "good" side either with a complete termination of agricultural activities or a social recuperation diminishing poverty. In some cases the soil is completely regenerated, in others it is not; yet soil degradation has not led to a total loss of productivity. Note that these are self-healing solutions, i.e., they are not induced by any kind of policy action. These solutions represent the complete recovery from the initial disturbances discussed above. It can be expected that these recoveries occur on sites with rather good natural conditions or a rather low dependence on agriculture; formally, this solution class is achieved if the decreasing agricultural activity reaches the landmark value *ms* before the increasing poverty exceeds the existential level *ex* or, in the case of initially elevated poverty, if poverty diminishes rapidly enough to fall below the existential level before agriculture becomes non-sustainable.

The classes discussed so far are achievable for the initial conditions on the outmost left in figure 4 only. They are not feasible if the qualitative values of both poverty and agriculture are initally set equal to or beyond their essential landmarks, *ex* and *ms*, respectively. The last solution class is possible for all initial states:

(5) Here the syndrome is "at its best": a highly active vicious circle finally leads to the overuse of the natural environment, connected with excessive poverty in spite of significant agricultural activity. The simultaneous occurrence of a high natural and a high social marginality is sufficient for this solution class to be achieved (see [30]). Note that this class of solutions is characterized by one unique bottleneck: $QS_B[(t_1, t_2)] = [\langle(ms, tot), \uparrow\rangle, \langle(0, out), \uparrow\rangle, \langle(ex, out), \updownarrow\rangle]$. It is interesting that though poverty might oscillate up and down, i.e., $qdir(\mathsf{Pov}, (t_1, t_2)) = \updownarrow$, within the open interval (ex, out) it cannot achieve the lower landmark *ex* with a possible exit from the vicious circle.

It can be stated that the dynamics of the functional pattern introduced as the SAHEL SYNDROME has both "fatal" and self-healing outcomes. As analagous behaviours occur for most diseases in medicine, we might verbosely interpret syndromes of Global Change as "clinical pictures of

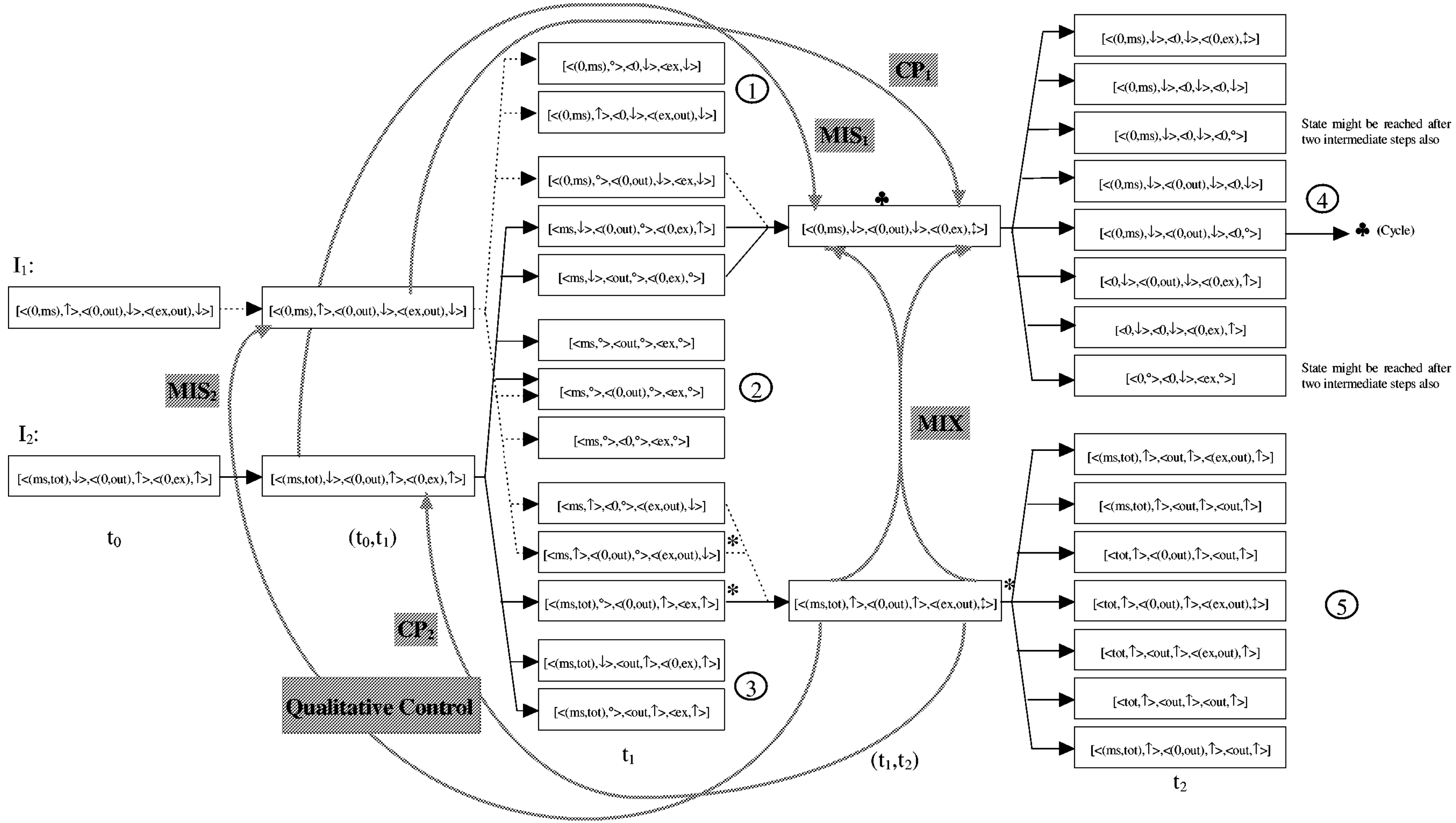


Figure 4. All possible solutions of the stand alone model for the core of the SAHEL SYNDROME. Each box represents a qualitative state of the system [Agr, Soil, Pov] indicated by the different qualitative values (see equations (8)–(10)). A single possible solution of the system is given by a single path through the tree. Besides the two initials on the outmost left, the three states at time t_1 indicated by an asterisk are possible initial conditions. Time increases from the left to the right and is given qualitatively in terms of landmark values at specific points t_i and the intervals between, indicated by (t_i, t_{i+1}). Note, however, that the specific points in time might be equal to infinity. The numbers refer to distinct solution classes discussed in the text; the thick grey lines represent the policy options discussed in section 4.3.

the Earth System": though a syndrome might disappear in the course of time due to intrinsic properties, it bears the potential for a ecologically and/or socially disastrous line of development.[6]

The fact that a total of 80 pathways through the tree exist for the five different initial conditions hints at the fact that the qualitative model of the core of the SAHEL SYNDROME is actually a meta-model exhibiting all possible dynamic solutions. It should be stressed that due to the completeness theorem of qualitative differential equations, we now know that all solutions of any model using ordinary differential equations to model the relation between poverty and soil degradation in a way as we do here, are covered by this solution tree. It would be a hard task to show this completeness by typical, quantitative modelling.

At this point the question of validation or – turned into a Popperian argument – falsification arises. If we start by considering a single syndrome only, we have to ask: does reality in regions with close interlinkage between smallholders agriculture and natural resources exhibit time behaviours which fit into the solution tree of figure 4? We can find these time behaviours not only within global or regional (national) statistical books and data banks, but also in local or regional case studies. In particular, we can use clauses like: "In the 50s poverty has increased, then it decreased for quite some time and now remains stable". This kind of statement can directly be compared to the solution tree. Thus, if we can find a regional multitude of these qualitative observations in the tree, we can speak about "non-falsification" of the basic mechanism implemented (see also [40]). Concerning the validation of the syndrome decomposition as a whole we have to ask: is there a limited set of qualitative models which are only weakly linked, i.e., they do *not* have to be run coupled but might use mutual abstractions of each other's output, and which are able to reproduce the local dynamics? Here, we have tentatively validated the model and refer the reader to an upcoming paper with a significant detailing of the model [40,46].

If we compare the results of our qualitative modelling attempt with the solutions of the linear quantitative model (equation (4)) we can say that there are solutions which are not realizable within the linear model. Consider, for example, the stationary class (2). Stationarity in the quantitative solution requires $S \equiv \text{const}$, $A \equiv \text{const}$. Therefore stationarity cannot be achieved dynamically but rather only by initialization. If, however, we had only the linear, or any other quantitative model, we would *not know whether we have covered all possible solutions (and/or classes) compatible with the given state of knowledge*. Therefore, the approach of qualitative reasoning chosen here seems to be a good starting point for an analysis of policy options, as we can be sure of covering all possible implications. At the end a combination of the qualitative approach with quantitative methods wherever possible will even enhance the capabilities of the approach [24].

[6] Visualize a flu where fever, though basic element of the healing process, might induce permanent heart or circular disturbances. From a philosophical point of view, an approach borrows some ideas from the GAIA hypothesis of Lovelock and his ideas on "planetary medicine" [29]. Yet, we think that our approach is more grounded, e.g., as it does *not* start from a homeostasis hypothesis.

4.3. Policy analysis by qualitative modelling

Usually the term *policy analysis* refers to political science investigations of the performance of governments or jurisdictions (such as the UN) in different policy *fields* (e.g., social or environmental policy) and at different *levels* (e.g., at a country or on the European level). The political system as such, its institutional framework (usually referred to by the term "polity"), is not the subject of this kind of research, neither is the political process and the interplay of power involved ("politics"). Discussing political measures by means of qualitative modelling within the present study concentrates upon *functional* aspects, i.e., the modifications of the basic dynamic behaviour of the syndrome.

Within the framework of ordinary differential equations one possibility of implementing policy measures would be to introduce a *control variable* into the corresponding equation (for a detailed discussion on the types of policies and the actors involved see [46]). Making a short excursion back to the general quantitative model (equation (1)) we might implement, say, a poverty-combating policy by writing

$$P = f_3(A, S) + C(t)$$

with $C(t)$ as the control function. The corresponding element in the QDE framework is the qualitative constraint given by equation (14d). The actual implications of the control, however, depend on the type of change of the qualitative variables; we can group the consequences into three classes whereby in this paper we want to concentrate on the last one:

(1) The external action changes the underlying quantitative values without changing the qualitative values. This would change the mutual relations between the underlying functions only, but would not modify the qualitative formulation of the model. Yet it might influence the branches taken by the system within the tree of development. Consider, for example, the state $QS[(t_0, t_1)] = [\langle(\mathit{ms}, \mathit{out}), \downarrow\rangle, \langle(0, \mathit{out}), \uparrow\rangle, \langle(0, \mathit{ex}), \uparrow\rangle]$ in figure 4. Appropriate measures to combat poverty, for example, might slow down impoverishment and thus can enhance the chance that the decreasing agricultural activity achieves a sustainable level before poverty becomes existential (first branching from the initial condition I_2). In this case, the system would take on one of the good class (4) solutions.

(2) New types of qualitative behaviour arise, if the qualitative values change and constitute new consistent qualitative states of the system which have not been feasible with the given initial conditions. Though possible

in principle, no such implications occur in the simple model of the SAHEL SYNDROME considered.

(3) The system changes from one type of qualitative behaviour to another without inducing completely new behaviours. In terms of the tree of development this corresponds to hopping between different branches and/or leaves of the tree. Henceforth we consider this type of behaviour in more detail.

We concentrate on two classes of policy actions: Combating Poverty (CP) and Mitigation of agricultural Impacts on Soils (MIS). In the literature a number of measures can be found which are related to one or the other of these classes:

Combating Poverty (CP). This is a task as multidimensional as poverty itself. Social policy offers important tools for this struggle. Nevertheless, experience gained from failing projects in developing countries suggest a broader approach, regarding poor people not only as (potential) victims of resource degradation, but also as potential and creative actors. Thus combating poverty means enabling and empowering people to take their fate into their own hands. Consequently, the focus in this point is not only to raise incomes, but also to improve the chances to convert entitlement [54] and assets (economic, social, cultural) into income. As rural poverty in many regions is an outcome of government policies showing an “urban bias” [3,28], a redirection towards rural areas – and especially the poor – is definitely helpful. Concrete policies include:

- land reform and securing land tenure rights,
- reform of agricultural price structure,
- reduction of tax load upon rural population,
- empowerment of rural population (e.g., by more participation, democratization, better regional governance),
- improving public health (sanitation, hospitals, vaccination, educational work etc.).

It is a research field on its own to study how the reduction of poverty can actually be ensured by one or the other of the policy options listed. Here we want to investigate the effectiveness of the overall strategy “Combat Poverty” with respect to the syndromes dynamics. We therefore assume that poverty is actually reduced and implement that by

$$\big\langle(ex, out), \cdot\big\rangle \xrightarrow{\text{CP}} \big\langle(0, ex), \cdot\big\rangle, \qquad (16)$$

i.e., we presume that action is successfully taken if poverty exceeds the existential level *ex*.

Mitigating agricultural Impacts on Soils (MIS). Agricultural activities (ploughing, fertilization, land clearance, herding, etc.) always affect the quality and structure of soils (nutrient content, thickness, water storage capacity, etc.). Whether these activities will improve or impair soils depends on many factors of human input and its organisation (technology, practices, local adaptation, etc.). Policies to mitigate these negative impacts will have to support technical equipment, techniques and skills that lead to more adaptive use and/or soil improvement. This includes in particular:

- no-tillage farming,
- agroforestry,
- contour ploughing,
- improvement of local farmer skills (e.g., by knowledge and technology transfer).

Again we assume the effectiveness of the policy actions. The action is implemented by fictitiously raising the quantitative value corresponding to *ms* which in qualitative terms can be written as

$$\big\langle(ms, tot), \cdot\big\rangle \xrightarrow{\text{MIS}} \big\langle(0, ms), \cdot\big\rangle. \qquad (17)$$

Correspondingly to the CP policy, we consider actions to take place if agricultural activity is not sustainable with respect to the soil.

This is of course only a small subset of policy options. A complete analysis of the core of the network of interrelations in figure 2 implies a somewhat larger number of classes of action. Yet the two examples chosen here are sufficient for illustrative purposes – and they bring about some interesting results. These results can be discussed using the “control transitions” indicated by the grey lines in figure 4 where the labels correspond to those in the following list:

CP_1: If poverty is successfully combated at a stage of the system’s behaviour when agriculture is still below *ms*, a *guaranteed* selection of solution class (4) takes place. Within the picture of initial perturbations giving rise to a specific initial condition, here I_1, the policy action results in a complete compensation of these initial perturbations.

MIS_1: Correspondingly, if the impact of agriculture on soils is effectively mitigated at an early stage (MIS_1) a sufficient compensation of the commencing effects of elevation of agricultural activity takes place and the syndrome evolves according to class (4).

CP_2: If the struggle against poverty is the only policy in case of significant agricultural activity, i.e. ($\mathsf{Agr} = \langle(ms, tot), \cdot\rangle$, the effect is not as unique as in cases MIS_1 and CP_1. As can be seen from figure 4, the effect of this policy option corresponds to a transition “back in time” and thus opens new alternatives, instead of the otherwise inevitable vicious circle. This set of alternative evolutions contains “negative” outcomes, i.e., the vicious circle (5) and class (3) with rapid soil degradation on the one hand, *and* “positive” or “neutral” outcomes, i.e., class (4) and the stationary solution class (2) on the other. The appearance of class (3) implies that even a permanent and successful combating of poverty might end in a complete loss of agricultural productivity, i.e., $\mathsf{Soil} = \langle \mathit{out}, \cdot \rangle$.

MIS_2: Reducing the impacts of agriculture on soils at a stage where poverty exceeds the existential level produces similar ambivalent results. Yet the new option space includes solution class (1) instead of (3) which implies that *no* rapid soil degradation (class (3)) is impending. This means that a repeatedly significant mitigation of the agricultural impact on soils would definitely prevent a fatal outcome from the dynamics of the syndrome. Yet we have to keep in mind that the bottleneck state QS_C is not preferable either, as there is significant poverty and soil degradation. Furthermore, the success would require a repeated employment of ever new agricultural techniques and practices whenever the critical situation QS_C arises – a difficult task.

MIX: Finally a *policy mix* with simultaneous reduction of poverty and agricultural impacts (option MIX) turns out to be most effective as a direct change-over to the self-healing branch (4) takes place. It has to be noted that this mix does not have to be applied simultaneously: the transition chains $\mathrm{MIS}_2 \rightarrow \mathrm{CP}_1$ and $\mathrm{CP}_2 \rightarrow \mathrm{MIS}_1$ are equally effective.

The analysis implies that the success of one or the other policy action is only implicitly time dependent, i.e., the strategy is *not* given by claims like “reduce the tax load of the rural population by 10% in the year 2000”. Instead implicit conditions for taking actions are formulated, e.g., “start a policy mix to reduce poverty significantly while agriculture is still at a low level”. Due to this implicitness, these strategies are general ones. The local or regional specificity has to be the subject of a subsequent investigation, taking into account more detailed information available for the respective region.

Some of these results are rather obvious, others are actually not. The simple fact that combating poverty, even if done continuously, cannot exclude soil degradation is surprising at least within the current model structure. On the other hand, the circumstance that the repeated improvement of agricultural techniques might prevent a fatal outcome is at least calling for some detailing [46]. Moreover, the systematic derivation of the politically favoured and facilely recommended policy mix as the most effective strategy is remarkable. Note, however, that the specification of effective policies is rather rough. It requires a successive step to analyse the best way to implement, say, the policy mix. Though the global analysis has helped to identify a “best strategy” its realization again depends on various, regionally specific circumstances [46].

It should be stressed that this analysis of basic policy strategies is structurally robust, it just depends on the qualitative interrelations as, e.g., specified in figure 2. In corresponding assessments using conventional modelling this structural robustness would not be guaranteed.

We have to underline that the analysis carried out takes into account the core of the syndrome only. As can be seen from figure 1 some more trends and interactions exist that can and in fact should be influenced. In order to prevent fatal outcomes of the syndromes dynamics, symptoms like *population growth*, *emancipation of women*, or *international indebtedness* have to be tackled. The qualitative-modelling based analysis of policies concerning this more realistic implementation of the syndrome has to be the subject of future modelling activities.

5. Conclusion and outlook

In this contribution we have tried to present a genuinely transdisciplinary approach to scientific reasoning about Global Change (GC) in a sufficiently self-contained way. The most important novel aspect of our approach is to employ *dynamic patterns* as the primary units of analysis, as such patterns seem to match best the heuristic granularity of the issues dealt with and the human ability to classify even weakly separable perceptions. This approach has a number of crucial implications.

First of all the patterning facilitates the general overview on Global Change. The vast multitude of phenomena involved in GC is no longer an amorphous mix, but rather can be perceived by a relatively small number of easy-to-grasp entities called *Syndromes of Global Change* [51]. Moreover, due to their functional character, syndromes represent natural objects for global environmental management – if the patterns can be identified rigorously. In this paper we have tried to illustrate how this identification might be carried out.

The identification of a single syndrome is basically carried out in three iteratively repeated steps:

(i) An inductive iteration by using soft and hard knowledge to specify the pattern in a weak sense. This is comparable to the first steps in the identification of new clinical pictures in medicine: symptoms are observed in a new unprecedented constellation. Yet the typification is iteratively modified on the basis of new observations – cases of illness in medicine; field studies, model results, data censi and analyses in Global Change. Yet it should be noted that the methodology presented is not restricted to the analysis of “Earth’s illnesses”, but might also be extended to investigation of more “positive” trends and developments.

(ii) A detailed analysis on the actual occurrence of the syndrome together with investigations on the conditions for a disposition or proneness to the pattern. Here the transdisciplinary and trans-sectoral character of the syndrome requires making use of modern techniques of acquisition and transformation of incomplete, uncertain and vague knowledge [22]. The goal is to produce world maps indicating where the syndrome actually occurs and where it might break out in the future. This *syndrome diagnosis* gives a broad and easily facilitated overview on the present processes of Global Change.

(iii) In order to get a picture on the possible time evolution of a syndrome, modelling techniques are implemented which are able to cope with the vague and uncertain knowledge. In the present paper we have employed the concept of qualitative differential equations [24]. It has been demonstrated that this concept is promising for the soft forecasting of syndrome dynamics: it produces entire classes of future development lines of the syndrome reflecting the aggregated character of the approach, i.e., though similar in pattern, the details might be different from region to region.

All three steps of the analysis together allow the explanatory power of the approach to be tested: is it possible to explain the core problems of Global Change [51] by a few basic dynamic patterns? How relevant is each syndrome with respect to a specific core problem? How do these patterns, and thus Global Change, evolve in time? The first results in the present paper on the SAHEL SYNDROME have shown that there is at least one important pattern: the geographical distribution of the syndrome, depicted in figure 3, exhibits the high relevance of rural poverty driven soil degradation and thus the need for appropriate policies able to stop this still increasing problem. It should be noted that the intensity assessment of figure 3 represents a necessary condition for the linear relationships between poverty, agricultural activity and soil degradation (see equation (3a)) to be valid. Combined with the restrictions on data quality and compatibility this implies some drawbacks on the applicability of the world map presented.

In section 4.3 it has been demonstrated that the combination of traditional policy analysis with methods of qualitative modelling brings forth a promising new method to evaluate policy options for global environmental management in light of the uncertain and vague knowledge being available. Though most of the results obtained for the SAHEL SYNDROME have long been debated in the scientific and political community, it is promising that the list of preferences of actions to be taken in order to impede rural poverty driven environmental degradation, has been confirmed by a systematic analysis in the form of a simple model using qualitative information only: according to our model the "best" strategy is an effective mix between improvements of agricultural techniques and practices on the one hand and poverty reducing policies on the other.

The system analysed in this paper is rather simple if compared to typical processes of Global Change, e.g., Climate Change. Experience shows that the analysis of larger systems by means of QDEs might easily become untractable if the constraints are not specified tightly enough. On the other hand, it seems particularly promising to combine qualitative methods with quantitative information wherever available. There is a number of approaches to this combination which should be considered, e.g., for a combined analysis of climate change [5,24]. Yet we think that the ideas given here suggest that the availability of qualitative information only can well be used in formal modelling of Global Change – a fact which in face of all the uncertainties in our knowledge has to be recognized as a significant value-adding signal for future endeavors in Global Change modelling.

Yet the iterative character of our approach has finally to be mentioned again. The current list of basic patterns of civilization–nature interactions (table 2) is definitely *not* the last word but only a first attempt – neither is the catalogue of symptoms. Therefore we ask the scientific community to take part in this discussion on major patterns of Global Change.

References

[1] J. Alcamo, ed., *IMAGE 2.0: Integrated Modelling of Global Climate Change* (Kluwer, Dordrecht, 1994).

[2] J. Alcamo and E. Kreilemans, Emission scenarios and global climate protection, Global Environ. Change 6 (1996) 305–334.

[3] R. Bates, *Markets and States in Tropical Africa: The Political Basis of Agricultural Policies* (University of California Press, 1981).

[4] U. Beck, *Die Entstehung des Politischen* (Suhrkamp Verlag, Frankfurt/Main, 1993).

[5] D. Berleant and B. Kuipers, Qualitative and quantitative simulation: Bridging the gap, Art. Intell. 95 (1998) 215-255.

[6] V. Bhaskar and A. Glyn, eds., *The North the South* (United Nations University Press, Tokyo, 1995).

[7] A. Block, J. Dehio, R. Lienenkamp, F. Reusswig and T. Siebe, Das "Kleine Tiger"-Syndrom: Wirtschaftliche Aufholprozesse und Umweltdegradation, Z. Angew. Umweltwiss. 10 (1997) 513–528.

[8] L.R. Brown, C. Flavin and H. Kane, *Vital Signs 1992 – The Trends That Are Shaping Our Future* (W.W. Norton, New York, 1992).

[9] M. Cassel-Gintz, M.K.B. Lüdeke, G. Petschel-Held, F. Reusswig, M. Plöchl, G. Lammel and H.J. Schellnhuber, Fuzzy logic based global assessment of the marginality of agricultural land use, Clim. Res. 8 (1997) 135–150.

[10] A.M.H. Clayton and N.J Radcliffe, *Sustainabilty – A Systems Approach* (Earthscan Publications, London, 1996).

[11] S.J. Cohen, Mackenzie basin impact study, Technical report, Environment Canada (1997).

[12] P.S. Dasgupta, Bevölkerungswachstum, Armut und Umwelt, Spektrum Wiss. 7 (1995) 54–59.

[13] L. Fleck, in: *Genesis and Development of a Scientific Fact*, eds. T.J. Krenn and R.K. Merton (Chicago/London, 1979).

[14] W. Franke, *Nutzpflanzenkunde – Nutzbare Gewächse der gemäßigten Breiten, Subtropen und Tropen* (Thieme, Stuttgart, 1992).

[15] A. Ganopolski, S. Rahmstorf, V. Petoukhov and M. Claussen, Simulation of modern and glacial climates with a coupled global climate model, Nature 391 (1998) 350–356.

[16] German Advisory Council on Global Change, *World in Transition – The Threat to Soils* (Economica, Bonn, 1994).

[17] German Advisory Council on Global Change, *World in Transition: Ways towards Global Environmental Solutions* (Springer, Berlin, 1996).

[18] German Advisory Council on Global Change, *World in Transition: Ways towards a Sustainable Use of Freshwater Resources* (Springer, Berlin, 1998).

[19] A. Haxeltine and I.C. Prentice, BIOME3: an equilibrium biosphere model based on ecophysiological constraints, resource availability and competition among plant functional types, Global Biogeochem. Cycles 10 (1996) 693–709.

[20] International Labour Organization, *World Labour Report 1994* (International Labour Office, Geneva, 1994).
[21] J.X. Kasperson, R.E. Kasperson and B.L. Turner II, eds., *Regions at Risk* (United Nations University Press, Tokyo, 1995).
[22] C. Kemke, Die Darstellung von ungenauem Wissen in taxonomischen Wissensbasen, KI Mag. 2 (1991) 12–19.
[23] J. Kropp, M.K.B. Lüdeke and F. Reusswig, Global analysis and distribution of unbalanced urbanization processes by usage of the fuzzy logic concept: the Favela syndrome, Int. J. Syst. Res. Inf. Sci., in press.
[24] B. Kuipers, *Qualitative Reasoning: Modeling and Simulation with Incomplete Knowlegde* (MIT Press, Cambridge, 1994).
[25] H. Lamprey, in: *Tropical Savannas*, ed. F. Bourliere (Kluwer, Dordrecht, 1983) p. 643.
[26] R. Leemans and G.J. van den Born, Determining the potential distribution of vegetation, crops and agricultural productivity, Water Air Soil Poll. 76 (1994) 133–161.
[27] H.J. Leonhard, ed., *Environment and the Poor: Development Strategies for a Common Agenda* (Transaction Books, New Brunswick, 1989).
[28] M. Lipton, *Why Poor People Stay Poor: Urban Bias and World Development* (Temple Smith, London, 1977).
[29] J. Lovelock, *GAIA – The Practical Science of Planetary Medicine* (Gaia Books, London).
[30] M.K.B. Lüdeke, O. Moldenhauer and G. Petschel-Held, Rural poverty driven soil degradation under climate change: The sensitivity of the disposition towards the Sahel Syndrome with respect to climate, Environmental Modeling and Assessment 4 (1999) 315–326.
[31] M.K.B. Lüdeke, F. Reusswig, M. Cassel-Gintz, A. Block, G. Lammel, W. Lass, R. Lienenkamp, G. Petschel-Held and M. Plöchl, Das Sahel-Syndrom, Armutsbedingte Übernutzung landwirtschaftlich marginaler Standorte, Reader for the QUESTIONS Status-Workshop, Potsdam (1996); http://www.pik-potsdam.de/~kropp/QUEST/sah_inh.html (German only).
[32] A.S. Manne, R. Mendelsohn and R.G. Richels, MERGE: A model for evaluating regional and global effects of GHG reduction policies, Energy Policy 23 (1995) 17–34.
[33] P. McCully, *Silenced Rivers. The Ecology and Politics of Large Dams* (Zed Books, London, 1996).
[34] J.A. McNeely, M. Gadgil, C. Leveque, C. Padoch and K. Redford, in: *Global Biodiversity Assessment*, eds. V.H. Heywood and R.T. Watson (Cambridge University Press, Cambridge) p. 711.
[35] D.H. Meadows, D.L. Meadows and J. Randers, *Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future* (Chelsea Green Press, London, 1992).
[36] W.D. Nordhaus, An optimal transition path for controlling greenhouse gases, Science 258 (1992) 1315–1319.
[37] W.D. Nordhaus and Z. Yang, *RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate Policy* (Yale University Press, New Haven, 1995).
[38] L.R. Oldeman, R.T.A. Hakkeling and W.G. Sombroek, World map of the status of human-induced soil degradation, An explanatory note (1990).
[39] F. Pearce, *The Dammed* (Bodley Head Books, London, 1992).
[40] G. Petschel-Held, M.K.B. Lüdeke and F. Reusswig, in: *Coping with Changing Environments*, eds. B. Lohnert and H. Geist (Ashgate, London), in press.
[41] D. Pimentel, C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri and R. Blair, Environmental and economic costs of soil erosion and conservation benefits, Science 267 (1995) 1117–1123.
[42] I.C. Prentice, W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud and A.M. Solomon, A global biome model based on plant physiology and dominance, soil properties and climate, J. Biogeogr. 19 (1992) 117–134.
[43] J. Quarrie, ed., *Earth Summit 1992* (Regency Press, London, 1992).
[44] M. Ravallion, *Poverty Comparisons* (Camberwell, 1994).
[45] A. Reenberg and B. Paarup-Laursen, Determinants for land use strategies in a Sahelian agroecosystem – anthropological and ecological geographical aspects of natural resource management, Agric. Syst. 53 (1997) 209–229.
[46] F. Reusswig, M.K.B. Lüdeke, O. Moldenhauer and G. Petschel-Held, First steps towards evaluating policy measures by qualitative modelling, to be submitted.
[47] P. Rogers, in: *Changes in Land Use and Land Cover: A Global Perspective*, eds. W.B. Meyer and B.L. Turner (Cambridge University Press, Cambridge, 1994).
[48] W.W. Rostow, *The Stages of Economic Growth*, 3rd ed. (Cambridge University Press, Cambridge, 1990).
[49] J. Rotmans and B. de Vries, *Perspectives on Global Change. The TARGETS Approach* (Cambridge University Press, Cambridge, 1997).
[50] H.-J. Schellnhuber, *Earth System Management* (Springer, Berlin, 1998).
[51] H.J. Schellnhuber, A. Block, M. Cassel-Gintz, J. Kropp, G. Lammel, W. Lass, R. Lienenkamp, C. Loose, M.K.B. Lüdeke, O. Moldenhauer, G. Petschel-Held, M. Plöchl and F. Reusswig, Syndromes of global change, GAIA 6 (1997) 19–34.
[52] J.B. Schor, in: *The North the South*, eds. V. Bhaskar and A. Glyn (United Nations University Press, Tokyo, 1995) p. 68.
[53] E.D. Schulze, K. Schilling and S. Nagarajah, Carbohydrate partioning in relation to whole plant production and water use of vigna unguiculate (l.) walp, Oecologia 58 (1983) 169–177.
[54] A. Sen, *Poverty and Famines. An Essay on Entitlement and Deprivation* (Oxford University Press, Oxford, 1981).
[55] J.D. Stryker, Technology, human pressure and ecology in the arid and semi-arid tropics, in: *Environment and the Poor: Development Strategies for a Common Agenda*, ed. H.J. Leonhard (Transaction Books, New Brunswick, 1989).
[56] The World Bank, *World Development Indicators* (1997).
[57] United Nations Development Programme, *Human Development Report* (Oxford University Press, Oxford, 1994).
[58] United Nations DPCSD, *Critical Trends – Global Change and Sustainable Development*, UN publication ST/ESA/255 (United Nations, New York, 1997).
[59] J.P. van der Sluijs, Integrated assessment models and the management of uncertainties, Technical Report WP-96-119, IIASA (1996).
[60] P. Wolf, C. Donawho and M. Kripke, Effect of sun-screen UV-radiation induced enhancement of melanoman growth in mice, J. Natl. Cancer Inst. 86 (1994) 99–105.
[61] World Commission on Environment and Development, *Our Common Future* (Oxford University Press, Oxford, 1987).
[62] World Resource Institute, *Welt-Ressourcen: Fakten–Daten–Trends, Ökonomisch-ökologische Zusammenhänge* (Deutsche Fassung, 1992).
[63] H.J. Zimmermann, *Fuzzy Set Theory and Its Applications* (Kluwer, Dordrecht, 1991).
[64] L. Zobler, A world soil file for global climate modelling, NASA Technical Memorandum 87802, Goddard Institute for Space Studies, New York (1986).