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Chapter 3

QUALITATIVE MODELING TECHNIQUES TO ASSESS PATTERNS OF GLOBAL CHANGE

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3.1 Introduction

New types of environmental problems are facing global society. Anthropogenic influence on the earth system approaches a dimension where it has a fundamental ascertainable impact on the system (Turner II et al. 1990). Today civilization is a significant factor of interference in the global ecosphere. The variety of involved mechanisms are characterized by complex trans-sectoral interdependencies and interrelationships (Schellnhuber and Kropp 1998). Therefore context-dependence of socio-ecological dynamics makes it extremely difficult to draw general conclusions about determinants for their robustness and for success or failure of management and/or steering strategies. There are considerable efforts to develop theories of socio-ecological systems and/or management success factors, e.g. based on large samples of case studies. Nevertheless, these approaches are often criticized for being too abstract for concrete environmental or institutional problems. The frequently stated reason for this circumstance is that every case has its distinct features which makes it problematic in order to compare it with other cases. This argument is based on idiographic traditions in science, which aim to identify the particularities of single case studies.

Such traditions deserve attention in their own right, in particular, if we consider that formal modeling disregards contextual differences, at least for technical issues of tractability. On the other hand, formal methods play an important role in nomothetic traditions, aimed at identifying results on a general level (e.g. fundamental laws of physics), and are therefore

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[1] Gerhard Petschel-Held was one of the most inspiring contributors to the syndrome concept during the recent years. In scientific discussions he always aimed to generalize his ideas beyond imagination at first and then pursuing a serious effort to gather a solid support for his theories and assumptions. On September 9th, 2005 he suddenly passed away in his office at the age of 42. In remembrance we wish to dedicate this chapter to him.

abstract. Having said this, it appears that although every case in a comparative case study is different, there can also be a strong resemblance. This knowledge may be very valuable for the design of strategies to deal with, e.g. CO_2 emission management or sustainable resource utilization.

Nevertheless in sustainability science we observe the phenomenon of complexity, i.e., we often have to consider exceptional dynamics involving innumerable system parts and a multitude of (non-linear) interrelations between the socio-economic and the natural sphere. Thus, it is more than ever essential to understand the most relevant mechanisms, driving forces, and/or feedback loops of systems, at least on an intermediate scale of complexity (cf. Schellnhuber et al. 2002). At this point any systematic analysis enters the "bottleneck of knowledge representation and derivation", since up to now no formal strategy exists on how to generalize from single observations. One reasonable strategy is to develop a quantitative and/or qualitative symbolic coding system (cf. e.g. Boardman 1995), but any representation may be imperfect and can be a source of errors (Davis et al. 1993).

We present archetypes as a pattern approach to this task. The general idea is that each problem class is structured by core interactions allowing to describe it as a typical pattern. The pattern approach is an essential technique to cope with complex situations and is also part of the learning process in human-environment interaction. It is the closest concept to the reality of brain representation and is based on both phylogeny and ontogeny. The brain of mammals is extremely efficient in reconstructing fragmentary patterns and in providing solutions for unknown situations by referring to analogous cases. This useful mechanism is, in particular, used by artificial neural networks (cf. Kropp and Schellnhuber 2007). In this chapter we will operationalize the pattern idea which has a long lasting history in different fields of science (see, for example, Polya 1954; Hayek 1973; Vámos 1995; Kelso 1997; Kropp et al. 2006a) for the assessment and simulation of complex global change pattern.

A first attempt to do this was the so-called syndrome approach, originated by the German Advisory Council on Global Change to the Federal Government (WBGU 1994), which was often criticized due to its less formal foundation and mainly heuristic characteristics. In a more general context of global change research, the syndrome approach was suggested as an instrument to analyze complex transsectoral phenomena. It provides a semi-quantitative and transsectoral overview of the "dynamical degradation patterns" that characterize contemporary human-environment interactions across the planet (cf. e.g. Schellnhuber et al. 1997; Schellnhuber et al. 2002). It decomposes the mega-process of "global change" into archetypal patterns, named syndromes, under the hypothesis that the web of relationships governing the planetary development is made up by a finite set of transsectoral sub-webs of distinct causal typology. It is a formidable task to elicit more knowledge on the complex interrelationships governing global change, but the syndrome approach can help to identify hot spots, as well as help identify key mechanisms. The latter is - at least - one precondition for the design of successful management regimes. We will reconsider this example by assuming archetypes as simple qualitative models which can (if necessary) be refined to the particularities of each case. We will show that by the utilization of adequate methodological concepts, a formal basis of the syndrome analysis is possible and will provide further insights.

This chapter is organized as follows. In Section 3.2 we introduce archetypes of social-ecological systems as a formal framework based on model ensembles. We also demonstrate, in an abstract way, how it can be used to pose well-defined and relevant questions within the domain of sustainability science. The framework is underpinned with an abstract semantic specification which relates it to established methods in case study research. In the subsequent Section 3.3 we introduce the syndrome concept. First we discuss the conceptualization, advantages, and shortcomings of the traditional syndrome approach (Section 3.3.1). This will be shown by the example of the Overexploitation syndrome. Subsequently, the semantic and formal aspects of three syndromes are illustrated in more detail. We start the formalization with the Overexploitation syndrome (Section 3.3.2) and present the same strategy for the Dust-Bowl syndrome, indicating the non-sustainable use of soils and water bodies, (Section 3.3.3) and for the Sahel syndrome dealing with the overuse of marginal land (Section 3.3.4). Then we again grasp the thread of the Overexploitation syndrome (Section 3.4) and introduce a multi-actor approach in order to derive further knowledge about successful management regimes. Finally, we summarize the strengths and limitations of this methodology and indicate directions for further research (Section 3.5).

3.2 Describing and Analyzing Archetypes as Model Ensembles

3.2.1 Model Ensembles

We understand archetypes as building blocks of society-nature interaction which appear in multiple case studies. The underlying hypothesis is that insights can be transferred from one case to another if the cases share archetypes. For this goal, an adequate notion of similarity is required, which can be specific but also generalizes features from other case studies, if they are of limited relevance. Such similarities introduce equivalence classes of models. This is necessary to examine real-world systems, which cannot be formally described in a unique way, also due to uncertainty. Although not concisely described as a general strategy, this style of reasoning is common – not only – in sustainability science, e.g. for parameter variation (e.g. Stainforth et al. 2005), model comparison (cf. Gregory et al. 2005), or scenario development (e.g. Nakićenović et al. 2000; Swart et al. 2004; MEA 2005). We formalize and generalize these ideas by introducing the notion of a model ensemble, which is a structured set of ordinary differential equations (ODE). These are considered simultaneously instead of investigating only single models.

A *model ensemble* $\mathcal{M}$ is defined as a set of functions $f : X \times \mathbb{R}_+ \to \mathbb{R}^n$ on a *state space* $X \subseteq R^n$. These functions are called *models*, each describing a possible configuration of a real-world system under investigation or one example of the pattern to be analyzed. The set $\mathcal{E}$ contains functions $x(\cdot) : \mathbb{R}_+ \to X$, being the space of *admissible trajectories* of the systems, e.g. $\mathcal{E} = C^1(\mathbb{R}_+, X)$. Each model $f \in \mathcal{M}$ defines a family of initial value problems

$$\begin{aligned} \dot{x} &= f(x,t), \\ x(0) &= x_0, \end{aligned}$$

with $x_0 \in X$. We call the set of all initial value problems given by a model ensemble the *systems of the model ensemble* $\mathcal{M}$. It is also possible to consider model ensembles which contain only autonomous models.

Of course, the systems of the model ensemble have (in general) different solutions. Thus, a *set* of trajectories is assigned to each initial value x_0. The set-valued *solution operator* $\mathcal{S}_{\mathcal{M}}(\cdot) : X \to \mathcal{P}(\mathcal{E})$ (of a model ensemble $\mathcal{M}$ with respect to a state space X and admissible trajectories $\mathcal{E}$), assigning to an initial state a subset of $\mathcal{E}$, is defined by

$$\mathcal{S}_{\mathcal{M}}(x_0) := \{x(\cdot) \in \mathcal{E} \mid x(0) = x_0, \exists f \in \mathcal{M}\ \forall t \in \mathbb{R}_+ : \dot{x}(t) = f(x(t),t)\}.$$

Depending on $\mathcal{E}$ it may be sufficient that the ODE holds almost everywhere. We call the elements of $\mathcal{S}_{\mathcal{M}}(X)$ the *solutions of the model ensemble* $\mathcal{M}$ (with respect to a state space X and admissible trajectories $\mathcal{E}$). If an application requires a very general model, $\mathcal{M}$ is the collection of all cases which have to be analyzed. Similarly, in the case of uncertainties, $\mathcal{M}$ is defined to subsume all systems which must be considered. These are given by the part of the knowledge base which is certain to a high degree, while variation is admitted for uncertain parameters, functions or processes. It is assumed that all these cases and/or all considered variations can be described as dynamical systems on the same state space X. The solution operator is closely related to the concept of an evolutionary system as defined by Aubin (1991) (cf. also Chapter 2 in this book for details). The main challenge in reasoning with model ensembles is to find relevant structures in $\mathcal{S}_{\mathcal{M}}(X)$. This includes:

1. representing a model ensemble in a way that is adequate to the modeler and allows for a formal treatment,
2. efficient algorithms to determine $\mathcal{S}_{\mathcal{M}}(X)$ from a (possibly infinite) model ensemble,
3. detecting structural features of the solutions of the model ensemble.

An example for the latter is to introduce normative settings in a formalized way by a partition $X = A \cup B$ of the state space into a preferable region A and a problematic region B. If for *all* $x(\cdot) \in \mathcal{S}_{\mathcal{M}}(x_0)$ and for all $t \geq 0$ the relation $x(t) \in B$ holds such that the system is "locked in" B due to its intrinsic dynamic interactions, it may be said that "a catastrophic outcome is unavoidable". Or if $\exists x(\cdot) \in \mathcal{S}_{\mathcal{M}}(x_0), t \geq 0 : x(t) \in A$, then "it is possible to sustain preferable conditions". Such features are very robust in that they hold for a whole model ensemble and not just one model. They are introduced as invariant or viable sets in Chapter 2. A discrete analogon is described in Section 3.2.3. We now provide some examples for model ensembles.

Example:
Let $\mathcal{M}$ contain only one function $f : X \times \mathbb{R}_+ \to \mathbb{R}^n$ which is Lipschitz on X, and let the admissible trajectories be $\mathcal{E} = C^1(\mathbb{R}_+, X)$. Then, $\mathcal{S}_{\mathcal{M}}(x_0)$ contains the usual solutions of the initial value problem with $x(0) = x_0$ which exist on $\mathbb{R}_+$.

Example:
Given a function $f : X \times \mathbb{R}_+ \times \mathbb{R}^n \to \mathbb{R}^n, (x,u) \mapsto f(x,u,t)$, depending on a control vector $u(t) \in U(x(t))$, and a finite set P of possible parameterizations, define the finite model ensemble

$$\mathcal{M} := \{f' \in C(X \times \mathbb{R}_+, \mathbb{R}^n) \mid f'(x,t) = f(x,t;p), p \in P\}.$$

Then, the solution operator, with respect to a set of admissible trajectories, provides all "scenario runs" for the different parameterizations.

Example:
In analogy to evolutionary systems as discussed in Chapter 2 for a given autonomous measurable function $f : X \times U \to \mathbb{R}^n, (x,u) \mapsto f(x,u)$, depending on a control vector $u(t) \in U(x(t))$ where $U(\cdot)$ assigns a set of admitted control vectors to each state, we define

$$\mathcal{M} := \{ f' : X \times \mathbb{R}_+ \to \mathbb{R}^n \text{ measurable } \mid \exists u \in U(x(t)) : f'(x,t) = f(x,u) \}.$$

Taking absolutely continuous functions as admissible trajectories, the solution operator $\mathcal{S}_{\mathcal{M}}(x_0)$ describes all trajectories starting from x_0 which result from any measurable open-loop control $u(\cdot) : \mathbb{R}_+ \to U$.

Example:
A further example (which will be introduced in detail below) are qualitative differential equations (QDEs). Basically, such a model ensemble is defined by a prescribed matrix of signs Σ via

$$\mathcal{M} = \{ f \in C^1(X, \mathbb{R}^n) \mid \forall x \in X : \text{ sgn } \mathcal{J}(f)(x) = \Sigma \}, \tag{3.1}$$

where $\mathcal{J}$ denotes the Jacobian and the sign operator is applied component wise. The signs of the Jacobian may, for example, result from a formalized causal-loop diagram (cf. Richardson 1986). We will see below how it can be used to define archetypes which describe the profit-driven or poverty-driven overexploitation of natural resources. If we take the set of continously differentiable functions which have only a finite number of critical points on any compact interval, $\mathcal{S}_{\mathcal{M}}(\cdot)$ can be computed by using the QSIM algorithm developed by Kuipers (1994) and his group at the University of Texas at Austin.

Within the framework of model ensembles, further questions can be posed which are highly relevant for sustainability science. If it is not possible to find relevant features common to all solutions of a model ensemble $\mathcal{M}$, we can try to identify subsets $\mathcal{M}' \subseteq \mathcal{M}$ for which such robust properties can be determined. The characterization of $\mathcal{M}'$ is associated with the discovery of structural features which bring about problematic or desirable system behavior. In other terms, conditions are found under which certain (sub)pattern evolve. If $\mathcal{M}$ is partially determined by certain control measures imposed on the system, and $\mathcal{M}'$ by alternative control measures, the differences between the solution operators $\mathcal{S}_{\mathcal{M}}(X)$ and $\mathcal{S}_{\mathcal{M}'}(X)$ are of interest.

3.2.2 Qualitative Differential Equations

Qualitative differential equations (QDEs) are a prominent methodology in qualitative modeling (Kuipers 1994). The basic idea of QDEs is not to determine all quantitative solutions, but all possible sequences of sign vectors $sgn(\dot{x})$ which can be brought about by at least one solution $x(\cdot) \in \mathcal{S}(X)$ (some further information, see below). These can be determined from the definition of $\mathcal{M}$ using the QSIM algorithm. The set of the possible sign vectors is finite, so that the result of the algorithm can be displayed as a directed state-transition graph, where each node represents a sign vector, and there is an edge between nodes v_1, v_2, if the sign vector v_2 occur as a direct successor of v_1 in at least one solution. The nodes in such a graph are also called *qualitative states*, and the edges *transitions*. The input for a modeling task is a QDE comprising the following parts:

1. a set of state variables;
2. a quantity space for each variable, specified in terms of an ordered set of symbolic *landmarks*;
3. a set of *constraints* expressing the algebraic, differential or monotonic relationships between the variables.

This defines the model ensemble in a twofold manner: (i) variables take values from the set of symbolic *landmarks* or intervals between landmarks. Each landmark represents a real number, e.g. maximum sustainable yield, of which the exact quantitative value may be unknown or uncertain. Nevertheless, it is analytically distinguished whether a grain yield or catch is above or below this threshold. The landmark or the interval between landmarks where the value of a variable is at a given time, is called its *qualitative magnitude*. (ii) Monotonic relationships specified between variables, e.g. that the yield is monotonically decreasing with a decreasing stock, are expressed by *constraints*. They introduce a (complex) relation between the qualitative magnitudes and the direction of change of the state variables in time (as seen in the example above).

Qualitative simulation achieves its result by performing a constraint satisfaction scheme (for a general introduction see Tsang 1993; Dechter 2003, for a more detailed description of constraint satisfaction problems (CSP) we refer to Chapter 5), where all combinations of qualitative magnitudes inconsistent with the constraints are filtered out. The outcome is a set of trajectories organized as a graph.

This so-called state-transition graph describes all possible solutions of a model ensemble $\mathcal{M}$ defined by the QDE in the following sense. The sign vectors of the velocity vector of a solution $x(t)$ with increasing t can be written as a well-defined sequence:

Definition 3.2.1 *For a given solution* $x(\cdot) \in \mathcal{S}_{\mathcal{M}}(x_0)$ *on* $[0,T]$ *we have an ordered sequence of sign jump points* (t_j) *with* $t_0 = 0$ *which subsequently contains all boundary points of the closures of all sets* $\{t \in [0,T] | [\dot{x}(t)] = v\}$ *with sign vectors* $v \in \{-,+\}^n$. *We construct a sequence of sign vectors* $\tilde{x} = (\tilde{x}_j) := \big([\dot{x}(\tau_j)]\big)$, *where we arbitrarily choose* $\tau_j \in (t_j, t_{j+1})$. *If the sequence* (t_j) *is finite with m elements, we choose* $\tau_m \in (t_m, T)$. *The sequence* $\tilde{x}$ *is called* abstraction *of* $x(\cdot)$.

Then, the state-transition graph is defined as

Definition 3.2.2 *Denote the set of the abstractions of the solutions by*

$$\tilde{\mathcal{S}}_{\mathcal{M}} := \{\tilde{x} \mid \exists x_0 \in X, x(\cdot) \in \mathcal{S}_{\mathcal{M}}(x_0) : \tilde{x} \textit{ is the abstraction of } x(\cdot)\}.$$

Then, the directed state-transition graph of the monotonic ensemble is defined by the nodes

$$V(G) := \{v \in \{-,+\}^n \mid \exists \tilde{x} \in \tilde{\mathcal{S}}_{\mathcal{M}}, j \in \mathbb{N} : \ \tilde{x}_j = v\},$$

called qualitative states, and the edges

$$E(G) := \{(v,w) \mid \exists \tilde{x} \in \tilde{\mathcal{S}}_{\mathcal{M}}, j \in \mathbb{N} : \ \tilde{x}_j = v \textit{ and } \tilde{x}_{j+1} = w\},$$

called qualitative transitions.

The guaranteed coverage theorem (an in-depth discussion of this theorem is beyond the scope of this paper, but cf. Kuipers 1994, p. 118) ensures that the algorithm computes a graph which contains the abstraction of *all* solutions of the model ensemble as a path. Obviously, due to the generality of the model ensemble, the state-transition graph usually has more than one unique path, and every path represents a set of quantitative trajectories development paths.

3.2.3 Viability Concepts

For larger model ensembles, the resulting state-transition graph can grow tremendously, such that various techniques are used for their analysis. One method is a graph theoretical analogon to concepts from viability theory (cf. Chapter 2), developed by Aubin (1991), which is increasingly used in sustainability science (see, for example, Kropp et al. 2004; Mullon et al. 2004; Cury et al. 2004; Eisenack et al. 2006a).

We briefly recall the necessary concepts from viability theory. Let $K \subseteq X$ be a subset of the the state space called a *constrained set*. A trajectory $x(\cdot)$ which remains in K, i.e. $\forall t : x(t) \in K$, is called *viable* in K. In the case of a model ensemble, multiple trajectories can start from a given initial value $x_0 \in K$. The set of all initial values, such that at least one trajectory is viable, is called the *viability kernel* of K. The set of initial values, such that all trajectories are viable, is called the *invariance kernel* of K.

In the context of a state-transition graph G, these definitions are modified as follows. The sets $V(G)$ and $E(G)$ are the nodes and edges of G, respectively, and the set-valued map $\Gamma : V(G) \to \mathcal{P}(V(G))$ assigns to every node the set of its successors.

Definition 3.2.3 *A set $D \subseteq V(G)$ is*

1. V*iable, if for all $v_0 \in D$*

$$\begin{aligned} &\exists \text{ path } v_0, \dots, v_i, \dots \text{ in } G \quad \forall i \geq 0 : v_i \in D \\ \text{or } &\exists \text{ path } v_0, \dots, v_m \text{ in } G : \Gamma(v_m) = \varnothing \text{ and } \forall i = 0, \dots, m : v_i \in D. \end{aligned}$$

2. I*nvariant, if for all $v_0 \in D$*

$$\forall \text{ paths } v_0, \dots, v_i, \dots \text{ in } G, i \geq 0 : v_i \in D.$$

3. N*o-return, if for all $v_0 \in D$*

$$\forall \text{ paths } v_0, \dots, v_m, \dots, v_i \text{ in } G \text{ with } v_m \in D, i \geq m : v_i \in D.$$

In a viable set, a path starts from every vertex which remains in the set. Invariant sets correspond to regions in the phase space which cannot be left once they are entered. The no-return set is a new concept here, describing sets which cannot be re-entered once they have been left. In the context of sustainability science, invariant sets correspond to robust facts under uncertainty or generality. Since there is no edge leaving an invariant set, no model of an ensemble has a solution leaving the associated region. In contrast, no-return sets correspond to a fragile configuration of states and velocities. Since there is no re-entering path, no solution of the model ensemble re-enters the region. A negative consequence holds for viable sets. If D is *not* viable, there are vertices in D where all successors are outside D, i.e. there is a region in the state and velocity space where any solution of the model ensemble necessarily leaves this region – a problematic situation if such a region is valued as positive.

No-return sets can be computed easily with standard algorithms from graph theory because it can be shown that every strongly connected component and every node which belongs to no strongly connected component is a no-return set, called a no-return basis. All other no-return sets are unions of such basis sets. Moreover, all invariant sets – which have the structure of a set lattice – can be generated from the no-return basis (see Eisenack 2006 for details).

3.3 Syndromes of Global Change

3.3.1 The Traditional Approach

The syndrome concept is a pattern approach which was developed by the German Advisory Council on Global Change to the Federal Government (WBGU 1994) and successively extended during the recent decade. The early syndrome concept was mainly based on expert elicitations and case study evaluations. With the help of this knowledge symptoms and interrelations are identified, which are necessary but not sufficient for the occurrence of the syndrome mechanism. This procedure ends up in a first systematization represented by a syndrome specific network of interrelations (Fig. 3.2, the black ellipses and bold arrows are the core of a syndrome). In its original form it comprises 16 syndromes (Tab. 3.1).

The names (Tab. 3.1, left column) are chosen either to sketch the main processes or to represent a paradigmatic area where the respective processes (Tab. 3.1, right column) can be observed. The syndromes are classified into three groups, reflecting more general properties of the underlying processes. These syndromes are non-exclusive, i.e. distinct syndromes can occur simultaneously at the same location and they can be coupled. The approach seeks for typical functional patterns of human-environment interactions by defining their essential mechanisms. In any case, this is a formidable task, since it implies an extensive evaluation of case studies, expert elicitations, and field work. Before we explain this in more detail, the following definitions have to be introduced which are essential for a general understanding of the syndrome concept.

- Symptoms are the basic entities for the description of the earth system with respect to problematic developments. A symptom is a functional aggregate of detailed variables describing a single sub-process of global change closely related to the human-environment interface. Examples include the loss of species diversity, urbanization, and freshwater scarcity. The concept works with approximately 80 symptoms associated to different spheres (atmosphere, social organization, science and technology, biosphere, etc.). They also include a temporal characteristics of the specific trends; thus, a symptom X is characterized by the tuple $(X, \dot{X}, \ddot{X}, \dddot{X}, \ldots)$.

Table 3.1. List of 16 Syndromes as proposed by the WBGU (1994). 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 civilizational outputs.

Syndrome Name	Utilization Syndromes
SAHEL	Overuse of marginal land
OVEREXPLOITATION	Overexploitation of natural ecosystems
RURAL EXODUS	Degradation through abandonment of traditional agricultural practices
DUST BOWL	Non-sustainable agro-industrial use of soils and bodies of water
KATANGA	Degradation through depletion of non-renewable resources
MASS TOURISM	Development and destruction of nature for recreational ends
SCORCHED EARTH	Environmental destruction through war and military action
	Development Syndromes
ARAL SEA	Damage of landscapes as a result of large-scale projects
GREEN REVOLUTION	Degradation through the transfer and introduction of inappropriate farming methods
ASIAN TIGER	Disregard for environmental standards in the course of rapid economic growth
FAVELA	Socio-ecological degradation through uncontrolled urban growth
URBAN SPRAWL	Destruction of landscapes through planned expansion of urban infrastructures
DISASTER	Singular anthropogenic environmental disasters with long-term impacts
	Sink Syndromes
SMOKESTACK	Environmental degradation through large-scale diffusion of long-lived substances
WASTE DUMPING	Environmental degradation through controlled and uncontrolled disposal of waste
CONTAMINATED LAND	Local contamination of environmental assets at industrial locations

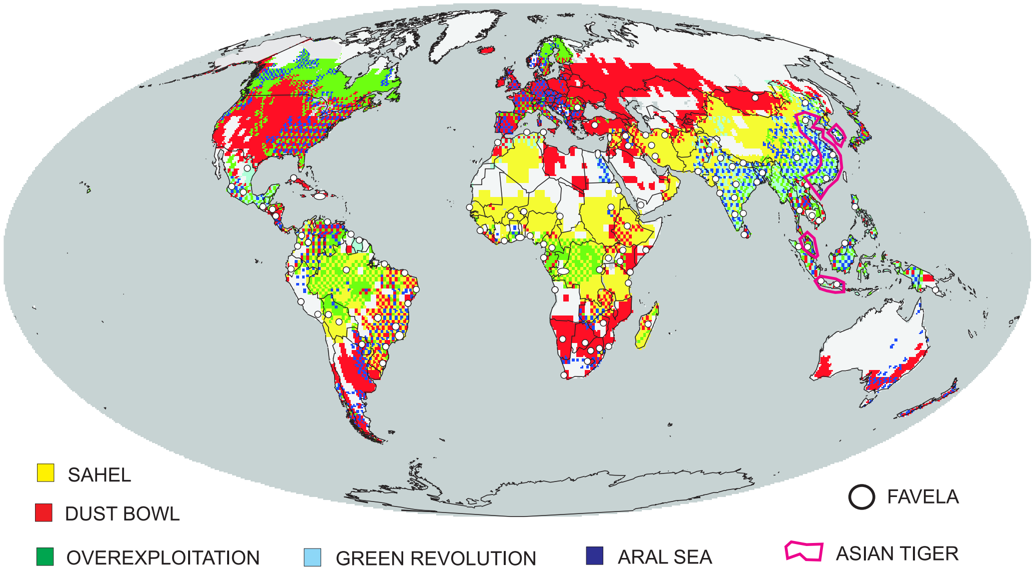

Figure 3.1. Overview of the global distribution of seven syndromes of global change. This image represents the achievements of the early syndrome approach and shows the local distribution of syndromatic patterns. This used some kind of heuristics and was only less formalized with respect to a homogenized methodology (after Lüdeke et al. 2004).

- Interrelations are the connecting elements for the symptoms and specify the causal relations. They are defined as monotonic relations, i.e. with increasing (enforcing) or decreasing (mitigating) effect.

This approach is nothing more than a qualitative and intuitive typifying approach, but it helps already to structure the single facets of global change in the global manifestation (see Fig. 3.1)[2]. The underlying working hypothesis was that the overall phenomenon of global change should not divided into regions, sectors, or processes but should be understood as a co-evolution of dynamical partial patterns of unmistakable character. Nevertheless, the description of these patterns is not sufficient, especially if the aim is to provide adequate policy advice. Therefore, some kind of formalization is needed, which we will apply for the subsequently discussed examples.

3.3.2 The Overexploitation Syndrome: Terrestrial and Marine Overexploitation

Before we start with the formal description of syndromes, we will present an example of overexploitation of terrestrial and marine natural resources, and how we can proceed from traditional to a more formal syndrome approach. As mentioned, syndromes are patterns of interactions, frequently with clear feedback character. It is a holistic and transsectoral approach, based on expert knowledge allowing to structure our knowledge on the mega-process of global change. These experts and our intuition allows us to define relevant

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[2] Discussions of specific syndromes can be found in Schellnhuber et al. 1997; Petschel-Held et al. 1999; Cassel-Gintz and Petschel-Held 2000; Kropp et al. 2001; Kropp et al. 2006b.

variables (symptoms) and interactions between them. Finally this ends up in a syndrome specific network of interrelations representing the essential mechanisms (see Fig. 3.2), e.g. "increasing exploitation of natural resources" leads to an "degradation of ecosystem's structure and function".

Marine overexploitation is a typical pattern of global environmental change posing threats to mankind's food security and marine biodiversity (MEA 2005). Fish contributes to, or exceeds, 50% of total animal proteins in a number of countries, such as Bangladesh, Cambodia, Congo, Indonesia, and Japan. Overall, fish provides more than 2.6 billion people with at least 20% of their average per capita intake of animal protein. The share of fish in total world animal protein supply amounted to 16% in 2001 (FAO 2004). Today, the impacts of overexploitation and the subsequent consequences are no longer locally nested, since 52% of marine stocks are exploited at their maximum sustainable level and 24% are overexploited or depleted (FAO 2004).

Global deforestation must be also regarded as an important threat to ecosystem services. Forest degradation is currently more extensive in the tropics than in the rest of the world (MEA 2005). There is multiple relevance of forest ecosystems, reaching from the cultural services for indigenous people and recreation in modern life, via regulating services for soils, biodiversity and climate, to provisioning services like water and wood. Overexploitation of these ecosystems may result in ecological regime shifts, soil degradation and destruction of livelihood. It is estimated that approximately half of global forests have been lost due to human activity since the end of the last ice age (Kapos et al. 2000). The non-sustainable path is characterized by strongly increasing timber extraction, fuelled by strong development of extraction and processing infrastructure, often in combination with lacking enforcement of natural protection laws and corruption (Cassel-Gintz and Petschel-Held 2000; Lüdeke et al. 2004). For example, in Amazonia, 80% of the deforested areas are located within 20 km of legally permitted roads (Barreto et al. 2006).

Common features of overexploited ecosystems include their inability to regenerate which results in further severe damage. One main driving force behind this dynamic include good profit opportunities for actors to utilize the ecosystem, but poverty alleviation plays an important role as well. In terms of numbers, forest conversation have mainly contributed to poverty mitigation throughout history (FAO 2003). However, any kind of overexploitation is characterized by a temporal discrepancy between socio-economic use and renewal of the resource (Cassel-Gintz and Petschel-Held 2000; Eisenack et al. 2006b), but learning concerning forests and marine resources, on the single actor's side as well as on the institutional side, has been identified as crucial for sustainable management (cf. Barreto et al. 2006).

Marine and terrestrial overexploitation syndrome share, amongst others, the symptoms "degradation of ecosystem structure and functioning", "expansion of infrastructure", and "policy failure", but differ in a set of accompanying problems (cf. Fig. 3.2). In the marine case, these are problems of the exact estimation of biomass, the migration of fish stocks and higher surveillance costs for management policies. Terrestrial overexploitation is associated with a larger proportion of non-mobile infrastructure which cannot be shifted to other regions, but to other uses (e.g. roads). Further, forcing factors like certain institutional settings, industry lobbyism and corruption strongly differ between ecosystems and countries and they are therefore rarely or unsuitably considered in analytical approaches

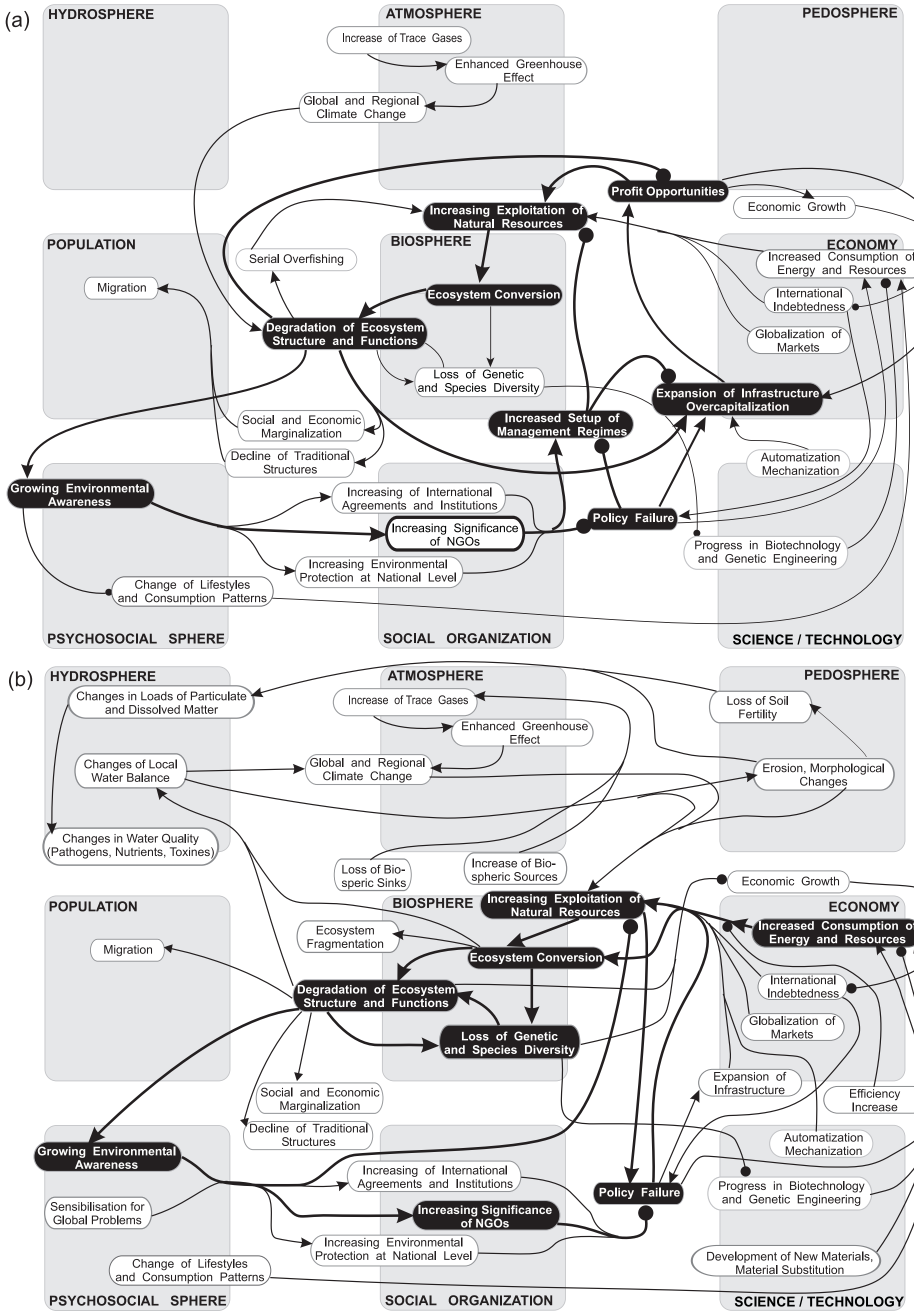

Figure 3.2. Syndrome specific networks of interrelations for the marine: (a) after Kropp et al. (2006b) and the terrestrial overexploitation syndrome: (b) courtesy of Cassel-Gintz and Petschel-Held (2000). The black ellipses (symptoms) considered as the necessary elements for an occurrence of a syndromatic pattern. Arrows indicate forcing and bullets mitigating mechanisms. Obviously there exist similarities, but also differences between the two expressions of the syndrome.

(cf. e.g. Smith et al. 2003; Anderies et al. 2004; Jentoft 2004). For advanced discussions on problems in fishery and forestry, see, for example, Hutchings et al. 1997; Nepstad et al. 1999; Munro 1999; Charles 2001; Eisenack and Kropp 2001; Potter 2002; Petersen 2002; Freire and Garcia-Allut 2000; Pauly et al. 2002; Wickham 2003; Smith et al. 2003; FAO 2003; Barreto et al. 2006 and also Chapter 8.

Whilst the the early syndrome approach mainly aims to diagnose potential hot-spots of hazardous developments, mitigation is closely connected with the need to enter into the fundamental dynamics of certain syndromes, in particular, if we are interested in an assessment of management strategies. We have shown in the previous Section that a variety of descriptions exist for resource overexploitation, which are not identical, but typically they share a common kernel of symptoms. Thus, a formal dynamic description of marine and terrestrial overexploitation, on an integrated and intermediate functional scale of complexity, is provided to assess the general development paths in forestry and fisheries. It is shown that in spite of uncertain process knowledge, a variety of conclusions can be drawn regarding sustainable resource use such that common patterns of forestry and fishery can be identified.

3.3.2.1 Basic Interactions

In the following section we present a formalized and updated version of the Overexploitation syndrome (cf. Tab. 3.1), which generalizes previous work of Kropp et al. (2006b) and Cassel-Gintz and Petschel-Held (2000). We introduce a common core pattern which combines both types of overexploitation. For that we use model ensembles which are solved with the QSIM algorithm and analyzed with viability criteria. In order to reveal more insights in the dynamics of this pattern, the archetypes will be examined in an abstract and systematic manner, i.e. by identification of those characteristic processes/features. Before we discuss the influence of single actors in syndrome analysis for the example, we will discuss the Sahel and the Dust-Bowl syndrome in subsequent sections in order to make it clear that our approach will work in general.

Broad profit opportunities are the starting point to unfold the overexploitation dynamic. There can be many reasons for this. Of course, there has to be an ecosystem which provides a rich but subtractable resource, which can be extracted at low costs or sold for high prices. In many cases, one cause for low costs is a *de jure* or *de facto* open access nature of the resource and available capital. Prices can be high due to (international) demand. Although profitable, the extraction requires the build-up of necessary infrastructure (e.g. boats, lorries sawmills, harbors), which partially cannot be converted to other uses. These mechanisms imply that multi-national corporations play an important role. With high investment infrastructure, extraction also increases, potentially beyond the regeneration capacity of the resource. This capacity itself is under pressure due to degradation and conversion of the whole (terrestrial or marine) ecosystems structure and functions, e.g. losses of biodiversity, changed water balance (in the terrestrial case), anthropogenically induced climate change, and shifts in the food-web. A socio-economic consequence of these processes is the displacement of traditional use, economic marginalization of indigenous people, a subsequent decline in the traditional structures, and finally migration. All these effects have the potential to reduce profit opportunities from resource extraction. Yet, a vicious cycle closes if these effects are over-compensated by the efficiency gains due to investment in more profitable infrastructure (Kropp et al. 2002; Eisenack et al. 2006b).

Further effects can be observed in the policy domain. A positive effect relates to the increasing environmental awareness which may lead to the establishment of management regulations and international agreements (e.g. UN 1995). However, in many cases, efficient management strategies fail or are simply rejected. (cf. Smith et al. 2003; Daw and Gray 2005). This can be related to various reasons, in particular high levels of corruption or lobby pressure on local and regional administrations. Usually, profits resulting from resource exploitation are made by transnational companies, which may be supported by national policies to develop export opportunities. If there are already high levels of infrastructure, there is a stronger pressure to keep money flowing to sustain returns on former investments. Thus, there are incentives for the public to reduce environmental standards or even to introduce subsidies for further infrastructure, leading to overcapitalization and resource overuse, thus closing another vicious cycle where private losses are compensated by the public.

The overexploitation dynamics can be attenuated by an increasing proportion of infrastructure, which is not directly related to resource extraction, but to marketing and transport of the resource. This is characterized by increasing overall costs which do not contribute to profits from extraction. Such infrastructure is spatially fixed to a region of the ecosystem, but can sometimes be converted to other uses, enforcing the dynamics of other syndromes. This is different for mobile extraction infrastructure, where investments need not be accounted for as sunk costs, since extraction units can be moved to other resources if the adverse effects of overexploitation make the industry less profitable. For the marine case, this is known as serial overfishing, indicating that fishing firms change target species or fishing grounds (Goñi 1998). It is also widely described in the literature for the terrestrial case (e.g. Lambin and Mertens 1997; Power 1996).

3.3.2.2 Model Ensemble

Based on a detailed literature survey and on previous work, we propose the following variables and relations for the syndrome core (see Tab. 3.2, Fig. 3.3). They can basically be grouped along three feedback cycles related to the processes outlined in the previous section, one related to investment in mobile extraction infrastructure (“infra”), another related to lobby pressure (“lobby”) and the last related to sunk costs of immobile infrastructure (“sunk”). For clarity, we omit consequences which are not part of a feedback cycle.

In the following we use the above qualitative description of the Overexploitation syndrome to set up a formal model using the model ensemble method and QDEs. This should provide additional insights into the syndrome dynamics without the need for quantitative data retrieval.

We focus on the “infra” and “lobby” feedback loop, where PROF-OPP, POL-PROF, EXTR-INFRA, EXPLOIT and RES occur. Here we assume the driving forces to be constant. To derive a formal model of this part of the influence diagram, more specifications need to be made. Since there is a considerable degree of freedom in this specified choice, the syndrome core as described by the causal-loop diagram (Fig. 3.3) represents a *very* general archetype, i.e. a general model ensemble $\tilde{\mathcal{M}}$. We narrow it down to a concisely defined,

Table 3.2. Core variables of the Overexploitation syndrome.

Variable	Definition
For feedback cycles:	
PROF-OPP (P)	Increasing profit opportunities. Expected profit rates for the extraction industry.
EXTR-INFRA (K)	Expansion of extraction infrastructure. Extraction units which enhance efficiency of exploitation, cannot be converted to other uses, but are mobile to be shifted to other ecosystems.
EXPLOIT (E)	Increasing resource exploitation. Extraction rate of resource under consideration.
RES (R)	Change of resource stock. The difference between natural regeneration and extraction rate.
OTHR-INFRA	Expansion of non-extraction infrastructure. Those investments which do not contribute to extraction efficiency and cannot be shifted to other regions.
POL-PROF (L)	Policies for profit opportunities. Political efforts to subsidize exploitation or decrease environmental regulations.
REC	Regional environmental change. Indirect effects of exploitation (as ecosystem conversion), and other regional environmental drivers which influence regeneration capacity.
For driving forces:	
GEC	Global environmental change. Changes affecting the regional regeneration capacity of the ecosystem, but which can only marginally be influenced by decisions on the regional level.
DEMAND	Increasing demand for resource consumption. Regional or international increase in demand for products from the resource, which may be indicated by high prices on the world market.
SUPPLY	Increasing supply of capital for resource extraction. Financial and physical capital available for investment in infrastructure.
TECH	Development of new extraction technology. Technological changes which alter efficiency or sustainability of exploitation.

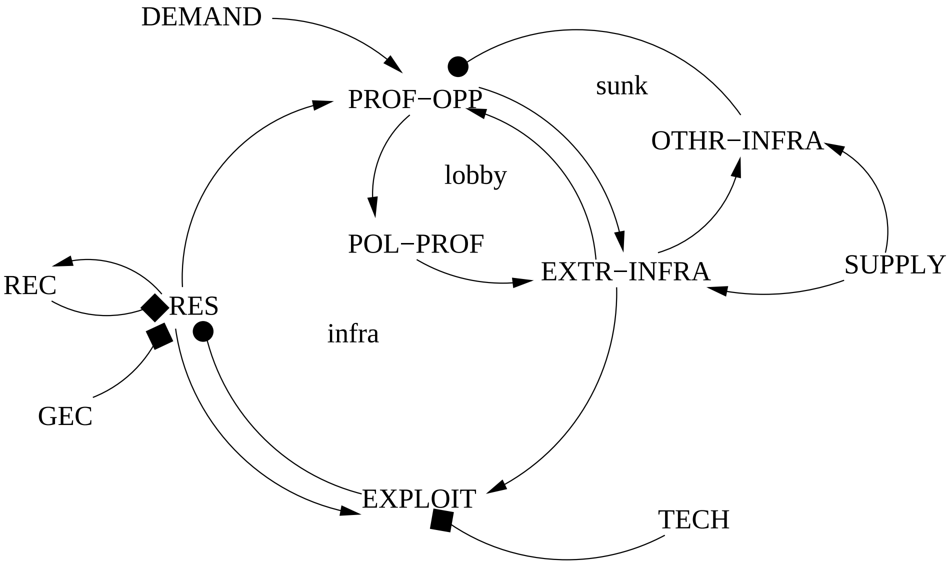

Figure 3.3. Core processes of the Overexploitation syndrome. Arrows denote enforcing, bullets attenuating and boxes ambiguous influences. The marks “infra”, “lobby” and “sunk” indicate feedback loops. Regarding the abbreviations cf. Tab. 3.2.

still infinite model ensemble $\mathcal{M} \subseteq \tilde{\mathcal{M}}$ by the following specification.

As state variables K, R, L we chose EXTR-INFRA, RES and POL-PROF, which represent stocks, while we assume PROF-OPP (P) and EXPLOIT (E) to be intermediate variables which determine flows:

$$
\begin{aligned}
\dot{K} &= f_1(P, L), \\
\dot{R} &= f_2(E), \\
\dot{L} &= f_3(P), \\
P &= f_4(K, R), \\
E &= f_5(K, R).
\end{aligned}
\tag{3.2}
$$

It is assumed that $D_P f_1, D_L f_1, D_P f_3 > 0, D_E f_2 < 0$ and $D_K f_4, D_R f_4, D_K f_5, D_R f_5 > 0$.[3] Moreover, we make the premise that there exists a regeneration capacity $m > 0$ so that $f_1(m) = 0$ and a political power threshold $z > 0$ with $f_3(z) = 0$. Beyond these assumptions, the exact derivatives, the regeneration capacity and investment threshold are not known quantitatively (due to uncertainties and due to differences between the social-ecological systems which should be covered by the archetype). In a systems dynamics context, the next step would be to decide on functional and parametric specifications to run a quantitative simulation of the syndrome dynamics. However, due to the generality of the syndrome archetype, we want to consider *all* systems which comply with the above requirements,

---

[3] For sake of readability $D_X Y$ is equivalent to $\partial Y / \partial X$.

yielding an infinite model ensemble

$$\begin{aligned}\mathcal{M} &= \{f = (f_1\, f_2\, f_3\, f_4\, f_5)^t \in C^1(\mathbb{R}^5_+, \mathbb{R}^5_+) \mid \\ &\qquad \exists m, z \in \mathbb{R}_+ : f_1(m) = f_3(z) = 0 \\ &\qquad \text{and} \, \forall x \in \mathbb{R}^5_+ : \operatorname{sgn}(\mathcal{J}(f)(x)) = \begin{pmatrix} 0 & 0 & + & + & 0 \\ 0 & 0 & 0 & 0 & - \\ 0 & 0 & 0 & + & 0 \\ + & + & 0 & 0 & 0 \\ + & + & 0 & 0 & 0 \end{pmatrix} \},\end{aligned} \tag{3.3}$$

where $\mathcal{J}$ denotes the Jacobian. By $x(\cdot) = (K(\cdot)\, R(\cdot)\, L(\cdot)\, P(\cdot)\, E(\cdot))^t$ we denote a trajectory of the state variables, so that the solution operator reads

$$\begin{aligned}\mathcal{S}(x) = \{x(\cdot) \in C^1(\mathbb{R}^5_+, \mathbb{R}^5_+) \mid& \\ & x(0) = x, \exists f \in \mathcal{M} \;\; \forall t \in R_+ : \\ & \dot{K}(t) = f_1(P(t), L(t)), \\ & \dot{R}(t) = f_2(E(t)), \\ & \dot{L}(t) = f_3(P(t)), \\ & P(t) = f_4(K(t), R(t)), \\ & E(t) = f_5(K(t), R(t))\}.\end{aligned} \tag{3.4}$$

It is defined for all initial values $x = (K R L P E)^T$ satisfying $P = f_4(K, R)$ and $E = f_5(K, R)$. The task to determine $\mathcal{S}(\mathbb{R}^5_+)$ can be solved using qualitative differential equations (see Section 3.2.2).

3.3.2.3 Results

The resulting state-transition graph has 52 nodes and 102 edges. There are many final states with $R = 0$ or $K = 0$ which differ only slightly. For a readable output of the graph, such final states and equilibrium states are omitted, which unlikely occur in a changing environment. The graph can be further simplified by automatically eliminating nodes which represent state variables being constant over a time interval (called non-analytical states), and eliminating edges which are not likely to occur (called marginal edges, see Eisenack 2006 for a justification, formalization, and algorithmic treatment). The outcome is a graph consisting of 8 nodes and 16 edges (see Fig. 3.4). It can easily be seen that the whole graph is strongly connected, meaning that it is – in principle – possible to reach every state from every state. This implies that it is possible that the system perpetuates infinitely through different stages. The are also bi-directional edges, such that the system may shift back and forth between two states forever. However, the definition of the state-transition graph only guarantees that for every edge between two nodes there exists at least one right-hand side in $\mathcal{M}$ such that the associated quantitative solution visits these qualitative states in the prescribed order (see Eisenack 2006 for details). Note that it is not claimed that *every* solution visits these states. For longer paths such a quantitative solution does not need to exist at all (making them so-called spurious behaviors, cf. Kuipers 1994). However, we may ask which subsets $\mathcal{M}' \subset \mathcal{M}$ can guarantee that every solution evolves along a given

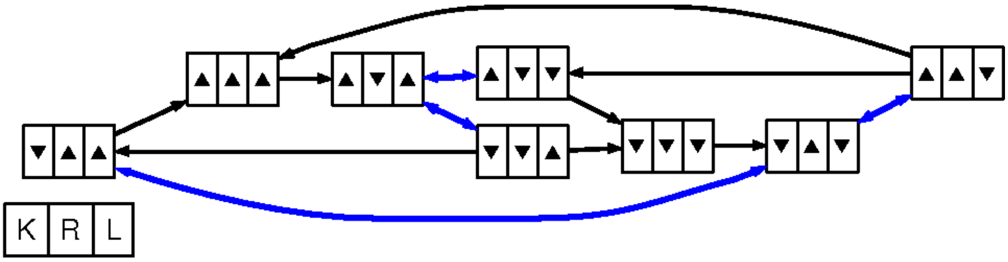

Figure 3.4. Simplified state-transition graph of the Overexploitation syndrome. Every box represents a qualitative state, where the signs $\operatorname{sgn}(\dot{K})$, $\operatorname{sgn}(\dot{R})$, $\operatorname{sgn}(\dot{L})$ are displayed, indicated by an upward or downward pointing triangle. Arrows between nodes indicate possible transitions between qualitative states. Catastrophic transitions are not depicted here, but $R = 0$ is a possible successor for all states with $\dot{R} < 0$, and $K = 0$ for all states with $\dot{K} < 0$.

path, or, alternatively, eliminates a given edge from the graph. We will provide a detailed example for the latter below.

But, for a first analysis, suppose that a system covered by the Overexploitation syndrome avoids a "catastrophic" outcome (as $R = 0$ or $K = 0$) for a long time: what can already be learned about the dynamics represented by this strongly connected graph? To make one striking result more obvious, we apply a projection as a further simplification technique to the graph. Here, only differences in some selected variables are considered, while nodes which only differ in other variables are "joined". If there exists a path in the projected graph, there also exists a path of corresponding nodes with the same qualitative values for the selected variables in the original graph (see Clancy 1997; Eisenack 2006 for a technical introduction).

By selecting K and E the existence of boom-and-bust cycles as a central feature of the Overexploitation syndrome becomes clear (see Fig. 3.5 and also Eisenack et al. 2006b). In the green state the resource is relatively unexploited and little capital is assigned to the extraction sector. However, the profitability of the forests or fish stocks attracts investment, leading to increasing extraction (growth phase). This state is left when exploitation is above the sustainable level, where net investment still takes place. This is due to the fact that the absolute resource stock is still high enough to sustain profits and, due to the lobby pressure, potentially decreasing profit rates are compensated (overexploitation phase). If the system is in this state for a longer time, extraction decreases because less of the resource is available. However, investment is still positive due to the lobby loop and the positive effect of accumulating extraction infrastructure on the profit opportunities, for example the effect caused by efficiency gains (orange red state, Fig. 3.5). It is thus interesting that expansion of infrastructure and contraction of resource use occur at the same time. A situation which can be characterized as built-up of overcapacities: Obviously more capital is used to obtain less from the resource. Depending on the rates of lobby pressure and extraction efficiency, the system may shift back to a state with increasing resource use. But it is also possible to move to the situation where the degrading resource shifts extraction costs to a level where investment becomes negative (collapse phase). If this results in extraction rates becoming sustainable again ($E < m$), the system cannot directly shift back to a level with decreasing capital and high exploitation. The resource has to regenerate first (recovery phase), and then the system may go through the whole cycle again with extraction beginning to increase and investment becoming positive thereafter. It should be noted that this boom-and-bust cycle can only develop in one direction (if we disregard some episodes of shifting back and forth). This is well-known for many case studies in fishery and forestry (e.g. Hilborn and Walters 1992; Power 1996).

It is also interesting to observe that every such cycle has to visit the state where overcapacities are built-up, making it a valid statement that every system described by the overexploitation syndrome inevitably undergoes such a period of increasing inefficiency – except for the case of a collapse (see Eisenack et al. 2006b, for a detailed economic analysis of this property for the case of unregulated fisheries).

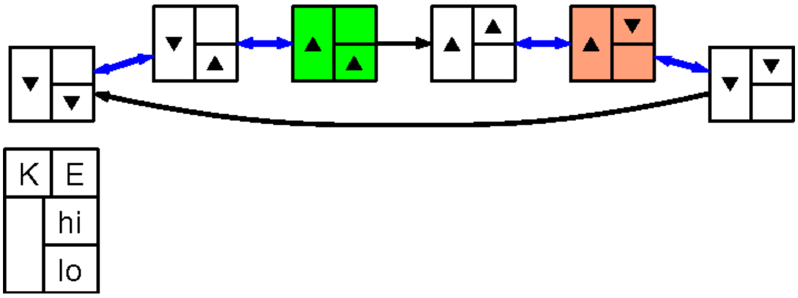

Figure 3.5. Projection of state-transition graph, considering only changes in $\dot{K}$ and $\dot{E}$ (for the symbols cf. Fig. 3.4). Triangles for $\dot{E}$ are in the upper part if $E > m$, and in the lower part for $E < m$. In the red state, extraction overcapacities are built-up. The green state is a typical initial state of a boom-and-bust cycle, beginning with an increasing but low exploitation rate and expanding investment in extraction infrastructure.

3.3.2.4 A Refined Model Ensemble

As indicated above it is important to know whether new structures appear if the model ensemble is narrowed down. This can provide important information for the management of a system governed by the archetype. We demonstrate this idea by introducing so called ordinal assumptions on the Jacobian and employing the viability concepts from Section 3.2.3 (cf. also Chapter 2). Define

$$\mathcal{M}' := \{f \in \mathcal{M} \mid \forall x \in \mathbb{R}^5_+ : D_R f_4(x) < D_K f_4(x) \,\text{and}\, D_K f_5(x) < D_R f_5(x)\}, \tag{3.5}$$

which implies the consideration of only those cases of the Overexploitation syndrome where profit expectations react more sensibly on changes in capital than on the state of the resource, while the marginal productivity of the extraction sector is stronger with respect to R than with capital K. We call such specification ordinal assumptions. These ordinal assumptions may hold because a given special case of the syndrome is considered, or they may be brought about by management interventions. In the following it is indicated how a state-transition graph for $\mathcal{M}'$ can be determined (see Fig. 3.6 for the result). At first, not only the signs $\operatorname{sgn}(\dot{K}), \operatorname{sgn}(\dot{R}), \operatorname{sgn}(\dot{L}), \operatorname{sgn}(\dot{P})$, $\operatorname{sgn}(\dot{E})$ are considered, but also whether

$$\delta := |\dot{K}| - |\dot{R}| \tag{3.6}$$

is positive or negative, distinguishing situations where extraction capacities change faster than the resource or vice versa. In the first step, every state in the original state-transition graph is split into two states with $\operatorname{sgn}(\delta) = (+)$ or $\operatorname{sgn}(\delta) = (-)$. These states inherit the edges of the original state and have a bi-directional edge between them. In the second step every edge which contradicts the ordinal assumptions is eliminated. For some edges there is a second elimination criterion, due to the introduction of δ. If, e.g. $\delta > 0$, it is impossible that $\dot{K}$ vanishes, so that every edge starting at such a state and where $\dot{K}$ changes its sign has to be refuted. Consider, for example, a state with $\dot{K} < 0 < \dot{R}$, $0 < \dot{L}$, and $0 < \delta$. From the original state-transition graph (leftmost box in Fig. 3.4), the following edges need to be assessed: (i) K begins to increase, (ii) L begins to decrease. Furthermore, it has to be checked if (iii) δ can become negative. The first edge has to be eliminated due to the reason given above. For edge (ii), note that

$$\begin{aligned}\ddot{L} &= D_P f_3 \dot{P} = D_P f_3 (D_K f_4 \dot{K} + D_R f_4 \dot{R}) \\ &= D_P f_3 (D_K f_4 |\dot{K}| \operatorname{sgn}(\dot{K}) + D_R f_4 |\dot{R}| \operatorname{sgn}(\dot{R}) \\ &= D_P f_3 (|\dot{R}|(D_K f_4 \operatorname{sgn}(\dot{K}) + D_R f_4 \operatorname{sgn}(\dot{R})) + D_K f_4 \operatorname{sgn}(\dot{K})\delta).\end{aligned} \tag{3.7}$$

Due to the signs of $\delta, \dot{K}, \dot{R}$ (which characterize the state), the signs of $D_P f_3, D_K f_4$, $D_K f_4$ (see definition of $\mathcal{M}$), and due to the ordinal assumption $D_K f_4 \dot{K} > D_R f_4 \dot{R}$, it follows that $\ddot{L} > 0$. Consequently, $\dot{L}$ cannot vanish and edge (ii) has to be eliminated. Regarding edge (iii), it is obvious that $\delta = \dot{K} + \dot{R}$, and that δ can only vanish if $\dot{K} = -\dot{R}$. Thus, by differentiating δ at the locus where $\delta = 0$, we obtain

$$\begin{aligned}\dot{\delta} &= \ddot{K} + \ddot{R} \\ &= D_P f_1 (D_K f_4 \dot{K} + D_R f_4 \dot{R}) + D_L f_1 \dot{L} + D_E f_5 (D_K f_5 \dot{K} + D_R f_5 \dot{R}) \\ &= \dot{K}(D_P f_1 (D_K f_4 - D_R f_4) + D_E f_5 (D_K f_5 - D_R f_5)) + D_L f_1 \dot{L}.\end{aligned} \tag{3.8}$$

Again, this expression is positive due to the ordinal assumptions, the properties of the model ensemble and the characteristics of the state under consideration. Therefore, also edge (iii) has to be eliminated. Since all three edges can be refuted, the state with $\dot{K} < 0 < \dot{R}$, $0 < \dot{L}$, and $0 < \delta$ has no successor, making it an invariant set as introduced in Section 3.2.3: no system included in $\mathcal{M}'$ can leave this situation where capital decreases – although the resource recovers and increasing lobby pressure compensates losses. These types of arguments can be applied to all other states, bringing about a structure where a boom-and-bust cycle still exists, but where several invariant sets and no-return sets can be entered (see Fig. 3.6). These irreversibly bring the system either to an economic (light blue boxes) or resource decline (red boxes). Interestingly, the states where over-capacities are built-up (orange boxes) lead to economic and not to resource decline, a situation which complements observations in many case studies (e.g. Goñi 1998). It should be stressed again that this property holds for *every* system contained in $\mathcal{M}'$, so that every system has a corresponding set of repellers and invariance kernels (cf. also Chapter 2).

3.3.2.5 Results

To come up with management conclusions for the Overexploitation syndrome, it must be stated that the ordinal assumptions made for $\mathcal{M}'$ do not provide a beneficial structure. In

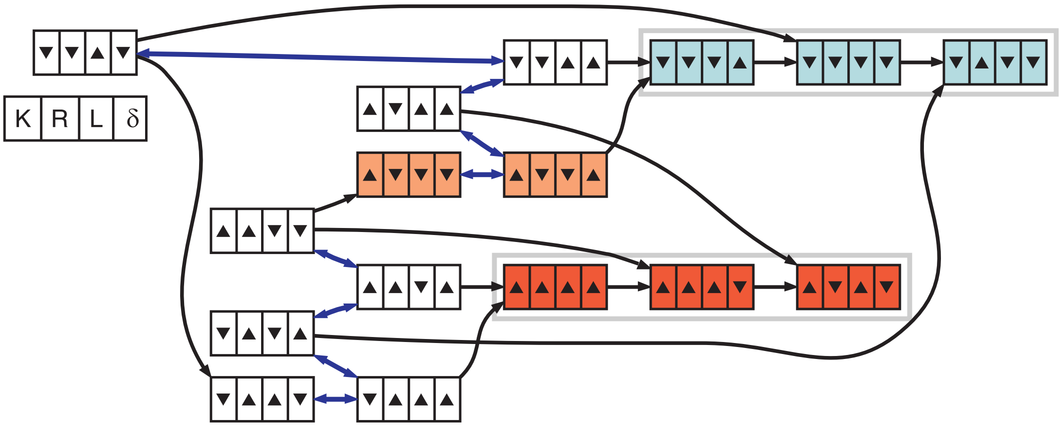

Figure 3.6. State-transition graph of the overexploitation syndrome under ordinal assumptions. The fourth column in each state denotes the sign of δ. The light blue and red states in grey boxes indicate no-return sets and invariant sets as discussed in the text. The states outside the grey boxes form a cycle, where in the orange boxes overcapacities emerge.

addition to the risks of resource depletion and diminishing capital which are already present in the more general case of $\mathcal{M}$, there are additional "cascades" of problematic irreversible developments which cannot easily be classified as such in an early stage. For example, without the result depicted in Fig. 3.6, it is not straightforward to forecast a continuous resource overuse at a stage where K, R and L increase and extraction infrastructure expands faster than the resource regenerates. If the properties expressed by the ordinal assumptions hold for a particular system, there should be interventions to change that, e.g. by introducing incentives to value resource quality in the formation of profit expectations more strongly. If the assumptions do not hold for another system, it should be avoided that they enter into force. Of course, for a systematic assessment of management options, further ordinal assumptions have to be considered – a task which remains to be done. Here algorithmic solutions are currently under development.

3.3.3 The Dust-Bowl Syndrome: Consequence of a Non-adapted Industrial Agriculture

As a further example we examine the interaction of environmentally destructive agricultural practices. A paradigmatic case were the historic droughts of the 1930s which transformed the Wheat Belt in the west and southwest of the U.S. into the so-called "Dust Bowl" - a dry landscape where dust storms prevailed. "Black blizzards" swept away the nutrient-rich topsoil of the region - like the storm on 9th May 1934, which transported approx. 350 million tonnes of dust from Montana and Wyoming via Dakota towards the east coast. The state-aided Dry Farming Program powered by the export drive to war-torn Europe had "prepared the ground" for the "Dust Bowl" phenomenon in the U.S.: through the massive use of machines (tractor, disc harrow, combine, etc.) the Great Plains were transformed into a monotonous "grain factory", whose broken-up surface remained exposed to the weather and unprotected for a large part of the year (Worster 1988). This kind of interaction of state subsidies with a modern, capital intensive agricultural sector is an important facet of the so called Dust-Bowl syndrome as defined by the WBGU (1995) which is in general characterized by a minimization of human labor input through the use of a wide range of machines on spacious, “cleared” agricultural areas and in “animal factories”. Attempts are made to maximize yield and capacity through

- mono-cultivation of highly productive kinds of plants,
- intensive livestock farming,
- large quantities of pesticides and medicine,
- intensive use of fertilizer and feed,
- intensive irrigation.

3.3.3.1 Basic Interactions

The main symptoms of the corresponding soil damage profile are (for a more detailed description see WBGU 2000):

- great susceptibility to wind and water erosion as a consequence of the considerable exposition times of the ploughed-up soil, combined with the low degree of structuring of the agricultural landscape;
- destabilization of turf and subsequent erosion through over-sized herds and overgrazing;
- loss of fertility due to deep ploughing, elimination of harvest wastes and monotonous crop rotation;
- reduction of soil drainage as a result of compaction by heavy agricultural machines;
- chemical soil pollution via overfertilisation and contamination (pesticides).

This causal pattern seems to be also relevant to the situation in Europe after World War II, where governmental subsidies within the framework of the European Economic Community were used to foster the modernization of the agricultural sector - which had a comparatively low productivity at this time. An important regulation tool was (and is) used to guarantee high producer prices which should increase and stabilize the income of the farmers and allow to increase productivity by investments in mechanization and chemisation. After some success in the beginning, economically and environmental problematic consequences occurred: tax payers subsidized the over-production of different agricultural goods (e.g. the “butter mountain” in the 1970s) and the capitalized agricultural production system generated the syndrome-typical environmental damages. To better understand this specific human-environment system we developed a qualitative system-analytical model which includes the most important variables and interactions as follows:

Agricultural income depends on production and producer prices. Above a particular income threshold the farmer is able to invest in his productivity which in the short term will increase his production with a positive feedback on his income. This positive feedback loop is dampened by two effects:

- when the total production satisfies the demand the guaranteed producer prices will be lowered by the regulating administration to avoid overproduction,
- with an increase in mechanization increasingly more money is needed to sustain and use this machinery.

In competition with this loop there is a negative feedback which works on intermediate time scales: as agricultural productivity depends also on the quality of natural resources (e.g. soil fertility and structure) and capital intensive farming often degrade these, either an increasing part of the income is necessary to compensate for these losses or the farmer will face long-term production losses despite his investments. Another important competition is between the wish of politicians and tax payers to reduce subsidized prices in case of overproduction on the one side and the efforts of the agrarian lobbyists to keep the income of their clientele high on the other. In general the success of the lobbyists depends of the importance of the agrarian sector in society and we will use here the total income of the farmers as an indicator. For a more detailed description of these mechanisms see the report of Lüdeke and Reusswig (1999) on the Dust-Bowl syndrome in Germany. In Tab. 3.3 we summarize the so far introduced variables and Fig. 3.7 shows the discussed relations between them as discussed above.

3.3.3.2 Model Ensemble

The following equations (3.9) describe the causal-loop diagram of Fig. 3.7 in the structure of a system of ordinary differential equations (for the abbreviations of the variables, see Tab. 3.3).

$$\begin{aligned} \dot{x}_1 &= g_1(x_1, x_5, x_6), \\ x_2 &= g_2(x_1, x_5), \\ \dot{x}_3 &= g_3(x_2, x_3, x_4), \\ \dot{x}_4 &= g_4(x_3), \\ x_5 &= g_5(x_3), \\ \dot{x}_6 &= g_6(x_2, x_6)\,. \end{aligned} \tag{3.9}$$

To adapt the model further to the European situation where the agrarian lobbyists were always able to avoid a significant reduction of subsidies, we integrate this into the model.

Table 3.3. Variables used in the description of the regulated agrarian system.

Variable		Definition
G_PRICE	x_1	politically guaranteed producer price for farmers
INCOME	x_2	income generated on the farm
PRODUCTIVITY	x_3	area or labor productivity of agriculture
ENV_DAMAGE	x_4	damage to environment and natural resources of the farm
PRODUCTION	x_5	agricultural production
INF_LOBBY	x_6	influence of agrarian lobbyists on guaranteed producer price

This reduces the solution space while losing only unrealistic trajectories. Another simplification is possible, because in Europe productivity determines production much more than the spatial extension of farming. Including this into the model one gets:

$$\begin{aligned}
\dot{x}_1 &= f_1(x_3),\\
x_2 &= f_2(x_1,x_3),\\
\dot{x}_3 &= f_3(x_2,x_3,x_4),\\
\dot{x}_4 &= f_4(x_3),
\end{aligned} \tag{3.10}$$

From this, the respective model ensemble can be defined. With

$$\begin{aligned}
\mathcal{F}_1 &= \{ f \in C^1(\mathbb{R}_+,\mathbb{R}_+) | \; \exists\, \mathsf{pr\_s} > 0 :\\
&\qquad \forall x < \mathsf{pr\_s} : D_x f < 0 \text{ and}\\
&\qquad \forall x \geq \mathsf{pr\_s} : f(x) = 0\}\\
\mathcal{F}_2 &= \{ f \in C^1(\mathbb{R}_+^2,\mathbb{R}_+) | \; \forall (x_1,x_2) \in \mathbb{R}_+^2 : D_{x_1} f \geq 0, D_{x_2} f \geq 0,\\
&\qquad f(0,x_2) = f(x_1,0) = 0\}\\
\mathcal{H}_1 &= \{ f \in C^1(\mathbb{R}_+,\mathbb{R}_+) | \; \exists\, \mathsf{i\_inv} > 0 :\\
&\qquad \forall x < \mathsf{i\_inv} : f(x) = 0 \text{ and}\\
&\qquad \forall x \geq \mathsf{i\_inv} : D_x f > 0\}\\
\mathcal{H}_2 &= \{ f \in C^1(\mathbb{R}_+,\mathbb{R}_+) | \; \exists\, \mathsf{ed\_c} > 0 :\\
&\qquad \forall x < \mathsf{ed\_c} : f(x) = 0 \text{ and}\\
&\qquad \forall x \geq \mathsf{ed\_c} : D_x f > 0\}\\
\mathcal{H}_3 &= \{ f \in C^1(\mathbb{R}_+,\mathbb{R}_+) | \; \exists\, \mathsf{pr\_c} > 0 :\\
&\qquad \forall x < \mathsf{pr\_c} : f(x) = 0 \text{ and}\\
&\qquad \forall x \geq \mathsf{pr\_c} : D_x f > 0\}\\
\mathcal{F}_3' &= \{ f \in C^1(\mathbb{R}_+^3,\mathbb{R}_+) | \; \forall (x_1,x_2,x_3) \in \mathbb{R}_+^3 :\\
&\qquad D_{x_1} f \geq 0, D_{x_2} f \geq 0, D_{x_3} f \geq 0,\\
\mathcal{F}_3 &= \{ f \in C^1(\mathbb{R}_+^3,\mathbb{R}_+) | \; \forall (x_1,x_2,x_3) :\\
&\qquad \exists g \in \mathcal{F}_3', f_1 \in \mathcal{H}_1, f_2 \in \mathcal{H}_2, f_3 \in \mathcal{H}_3 :\\
&\qquad f(x_1,x_2,x_3) = g(f_1(x_1), f_2(x_2), f_3(x_3))\}\\
\mathcal{F}_4 &= \{ f \in C^1(\mathbb{R}_+,\mathbb{R}_+) | \; \exists\, \mathsf{pr\_c} > 0 :\\
&\qquad \forall x < \mathsf{pr\_c} : f(x) = 0 \text{ and}\\
&\qquad \forall x \geq \mathsf{pr\_c} : D_x f > 0\}
\end{aligned} \tag{3.11}$$

where pr_s, pr_c, ed_c denote the relevant threshold values (landmarks). The model ensemble is defined by

$$\mathcal{M} = \{ f = (f_1\; f_2\; f_3\; f_4\; f_5) | f_1 \in \mathcal{F}_1, f_2 \in \mathcal{F}_2, f_3 \in \mathcal{F}_3, f_4 \in \mathcal{F}_4 \}$$

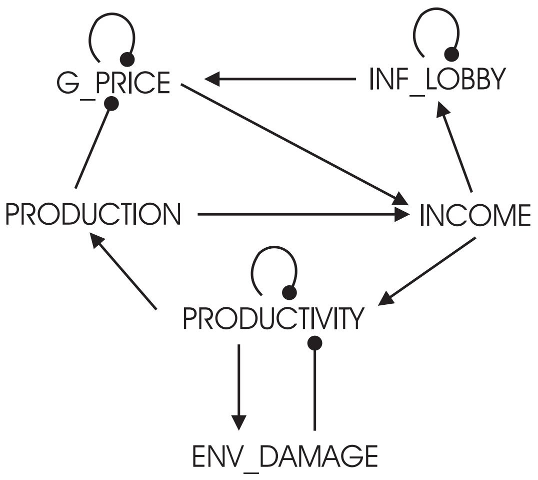

Figure 3.7. Cause-effect diagram (causal-loop diagram) for a (price-)regulated agrarian system as, e.g., realized in the EEC/EU since World War II. Arrows denote enforcing, bullets attenuating forces. Note the self-attenuation of productivity (e.g. by decay of machines), guaranteed prices (the higher they are the larger is the public pressure to reduce them) and the influence of the agrarian lobbyists (which has to be actively sustained by the agrarian sector).

with the respective solution operator (cf. also Section 3.3.2.2)

$$\begin{aligned}\mathcal{S}(x) = \{x(\cdot) \in C^1(\mathbb{R}^4_+, \mathbb{R}^4_+) \mid \\ x(0) = x, \exists f \in \mathcal{M}\ \forall t \in R_+ : \\ \dot{x}_1(t) &= f_1(x_3(t)), \\ x_2(t) &= f_2(x_1(t), x_3(t)), \\ \dot{x}_3(t) &= f_3(x_2(t), x_3(t), x_4(t)), \\ \dot{x}_4 &= f_4(x_3(t))\}.\end{aligned} \tag{3.12}$$

3.3.3.3 Results

Using the QSIM algorithm, one gets all possible qualitative trajectories, which are summarized in Fig. 3.8. Here, state (a) in the lower left corner characterizes the immediate post-war situation in Europe: guaranteed prices start to increase, farm income also starts to increase but is still below the threshold i_inv necessary for investment in productivity increases. Productivity is below the value where significant resource damage occurs and the directly related production is below the demand, justifying further increase in guaranteed prices. The necessary successor state (b) reproduces the observed initial success of the regulation: INCOME exceeds i_inv and productivity starts to increase. But already state (c) which follows necessarily, shows an ambivalent situation: once the productivity has transgressed the threshold pr_c where significant costs occur to sustain it the further income development becomes undefined with respect to direction and magnitude, i.e. the system no longer inherently guarantees a secure livelihood for the farmers. This state is closely connected with four other states which constitute a no-return set (NRS1), i.e. when the trajectory leaves this set, it can never return to it as long as it governed by the assumed relations. State (d) which can follow (c) depicts the most positive situation in NRS1: stable and high income of the farmers, stable and high productivity at pr_c, which generates sufficient production and a stop of the increase of guaranteed prices.

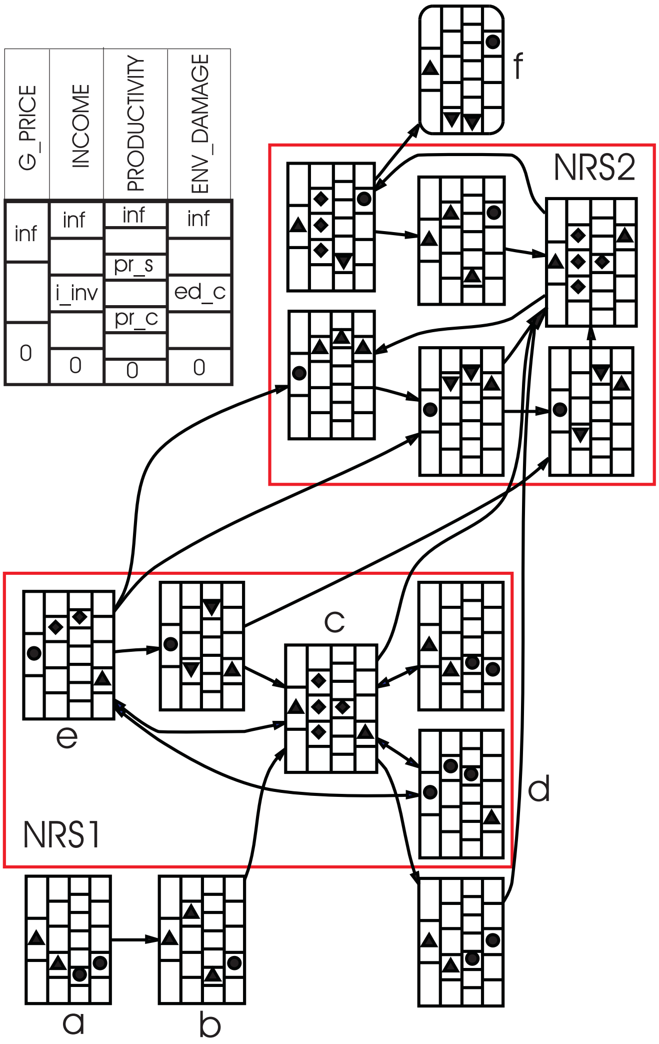

Figure 3.8. All qualitative trajectories which are in accordance with the cause-effect diagram for the (price-) regulated agrarian system as given in Fig. 3.7. Each qualitative state is symbolized by a rectangle which is subdivided into four columns denoting the different variables with respect to their qualitative magnitude (see state definition in the upper left corner) and trend direction. A rhombus stands for an undefined direction, the bullet for constancy in time. The large arrows denote possible sequences of states. No-return sets are symbolized by the large red rectangles.

But this situation is not systemically stable: it may either return back into (c) or proceed into (e), depicting subsidized overproduction - the “butter mountain” case. As long the trajectory remains in NRS1, productivity remains above (or at) pr_c and resource/environmental damage below ed_c. Unfortunately the system allows several ways of transgression into NRS2 which is characterized by ENV_DAMAGE above ed_c, a situation where the reduced quality of the resource influences productivity negatively, resulting either in additional costs to compensate for this or in productivity losses. This generates a much more unstable situation for productivity than in NRS1 while the income stability is similarly poor. So, the policy of NRS1 is preferable because at least the aim of productivity increase is realized while the objective of stabilizing the farmer’s income is not reached. After entering NRS2 there is no way back to a secured high productivity situation. Instead environmental damage and increasing subsidies have to be expected and – even worse – state (f) can be reached: the total collapse of the agrarian system becomes possible, constituted by the breakdown of production, income and resources. Comparing this model–deduced structure of the state space with the actual observed situation of the agrarian system in Europe, it is probably located within NRS2, i.e. only structural changes will allow the improvement of the situation. This is because the endogenous dynamics will end up in the same situation after temporary interventions which generate only a “jump” in the state space. The proposed model can serve as a means of policy assessment with respect to such structural changes which will certainly have to be more complex than the simple recipe of “de-regulation” which throws back the system into the unsolvable contradiction between short-term profit interests and mid- to long-term environmental impacts. Obviously an intelligent re-structuring of regulations is the way to go as, e.g., suggested by the SRU (1998).

3.3.4 The Sahel Syndrome

The third example systematized in this manner is a pattern which is described by the Sahel syndrome (cf. Tab. 3.1). It addresses the field of the closely related environmental, economical, social and political aspects of smallholder farming in developing countries – a field where anthropogenic environmental change often feeds back rather rapidly on the socio-economic situation of the actors – and where the latter are confronted with strong constraints like social and economic marginalization, population pressure and fragile natural production conditions (Lüdeke et al. 1999).

3.3.4.1 Basic Interactions

From several studies on the semantic aspects, a formal model is teased out which describes the qualitative functional relationships between labor allocation into off-farm labor, resource conservation measures and short-term yield maximizing activities and natural degradation, income and poverty, market prices, access to resources, population growth and some further relevant variables. Figure 3.9 shows an aggregated synopsis of relations as for example stated by Leonhard (1989), Kates and Haarman (1992), Kasperson et al. (1995), and others dealing with the environment–poverty problem. This scheme is supposed to constitute “mental maps” (cause-effect diagram) (cf. Fig. 3.9) of the most important mech-

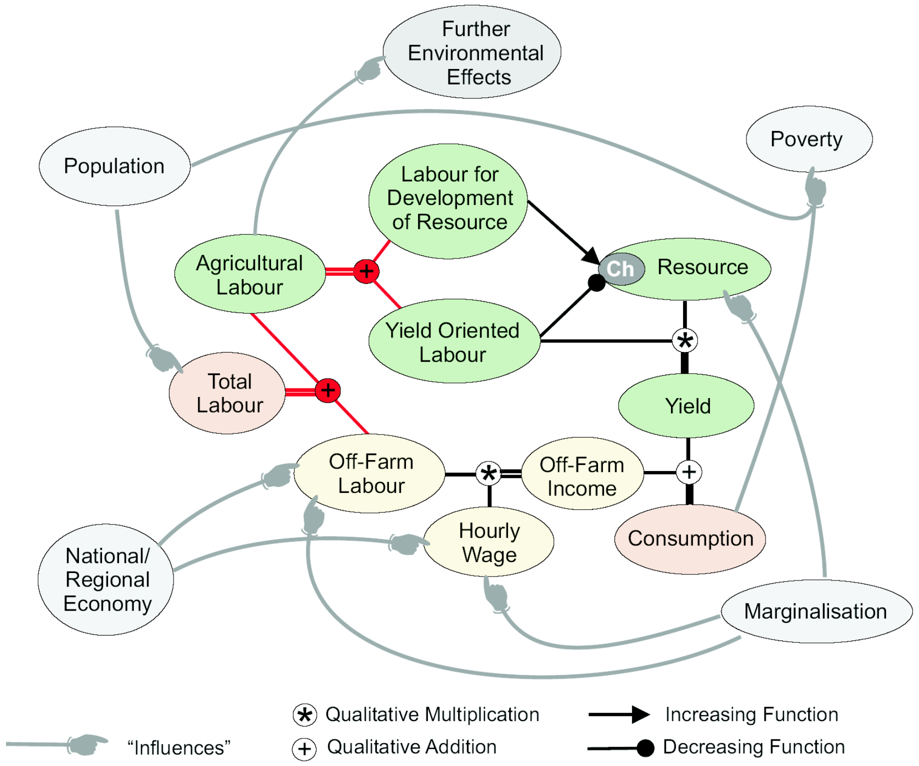

Figure 3.9. Mental map (causal-loop diagram) of smallholder agriculture. In contrast to Figs. 3.3 and 3.7 here potential side effects are introduced by a "trigger finger". Furthermore qualitative nexuses are shown.

anisms underlying the dynamics of smallholder agriculture in an intermediate functional resolution.

In the agricultural subsystem yield depends on the state of the resource and the directly yield-oriented labor investment, i.e. it increases with both factors and vanishes if one factor becomes zero. We subsequently call this relation "qualitative multiplication" (cf. Kuipers 1994). Under "yield oriented labor" we subsume frequent tillage and weeding, the shortening of fallow periods, intensive irrigation etc. All these measures can increase the annual yield in the short term but put pressure on the resource, leading to resource degradation by erosion, soil fertility losses, salinization etc. On the other hand we have agricultural activities which counteract these degradation trends as terracing, drainage ditches, hedge plantings, mulching etc. We include here not only activities for resource conservation, but also endogenous technological progress which increases the efficiency of the resource and obviously needs some engagement by the farmer, a process which – in our qualitative framework – can be represented by developing the resource (in that way we map Boserupian aspects of the dynamics). These two kinds of activities constitute the pool of agricultural labor – and decreasing one of them means increasing the other (under constant total agricultural labor). This simple relation is called "qualitative addition" (Kuipers 1994).

The second realm of smallholder activities is the off-farm labor: here an off-farm income is generated via the hourly wage. This income, measured in units of agricultural produce, together with the obtained yield adds up to the total consumption. The total available labor is divided into the labor on the own farm (as land manager) and off-farm labor. Furthermore the qualitative model shown in Fig. 3.9 considers population which, on the one hand, generates the total available labor and, on the other hand, divides the total consumption into per capita consumption, sometimes resulting in poverty. Marginalization of smallholders influences their access to resources as well as to wage labor (e.g. via ethnic discrimination). The total availability of wage labor and the hourly wage depend on trends in the national economy.

How can such a mental map be used for any (weak) kind of prediction, which is the basis for any assessment of policy options? One way would be to quantify the variables and relations and to introduce a utility optimization hypothesis for the two decision problems considered in the qualitative model: the allocation of labor between on farm vs. off-farm and between short term yield and resource development (red symbols in Fig. 3.9). This kind of approach was chosen by many modelers (e.g. Barbier 1990; Barrett 1991; Grepperud 1997) – but both the optimization hypothesis and the possibility of adequate quantification are questionable. In particular under the rapid change of the conditions of smallholder agriculture in developing countries the argument that an optimization approach would model the result of a long lasting evolution process leading to an optimal adaptation of the actor's strategy seems implausible. In contrast to these attempts we define qualitative behavior rules which are far less sophisticated:

- the reallocation between on- and off-farm labor is performed according to the difference between present labor productivity of the agricultural and the off-farm activity,
- the reallocation between yield oriented labor and labor for the development/conservation of the resource is governed by the relation of present per capita consumption and a critical level of consumption, c_k, below which conservational labor is reduced.

According to the "mental map" in Fig. 3.9 and the allocation rules stated above we get the following structure in terms of the variables defined in Tab. 3.4:

$$\begin{aligned}
\frac{dR}{dt} &= g_1(LY, LQ)\\
\frac{dLT}{dt} &= g_2(t)\\
\frac{dLW}{dt} &= g_3\left(w - \frac{Y}{LY}\right)\\
\frac{dv}{dt} &= g_4\left(\frac{Y + w\cdot LW}{LT}, c_\mathrm{k}\right)
\end{aligned}\tag{3.13}$$

Due to $LT = LW + LY + LQ$, the number of relevant variables can be reduced to four. We chose (R, LT, LW, v), where $v = \frac{LQ}{LY}$. The latter is appropriate as the competing influences of LY and LQ on the change of R are best represented by the relation of the different work

Table 3.4. Variables of the qualitative smallholder model.

Definition	Variable
Resource quality (e.g. soil)	R
Total available labor	LT
Off-farm labor	LW
Yield oriented labor	LY
Hourly wage	w
Labor for development of R	LQ
Yield	Y
Consumption per capita	c
critical value for C	c_k

inputs. After this variable transformation we obtain the following set of ordinary differential equations

$$\begin{aligned}\frac{dR}{dt} &= f_1(v)\\ \frac{dLT}{dt} &= f_2(t)\\ \frac{dLW}{dt} &= f_3(R,LT,LW,v)\\ \frac{dv}{dt} &= f_4(R,LT,LW,v)\end{aligned} \tag{3.14}$$

which belongs to the following model ensemble:

$$\begin{aligned}\mathcal{M} &= \{f = (f_1\ f_2\ f_3\ f_4)^t \in C^1(\mathbb{R}^4_+,\mathbb{R}^4_+) \mid \\ &\forall x \in \mathbb{R}^4_+ : \mathrm{sgn}(\mathcal{J}(f)(x)) = \begin{pmatrix} 0 & 0 & 0 & + \\ 0 & 0 & 0 & 0 \\ - & ? & ? & ? \\ + & ? & ? & - \end{pmatrix}.\end{aligned} \tag{3.15}$$

Now the number of unclear signs in the Jacobian can be significantly reduced by introducing the assumption that the labor productivity of agriculture, Y/LY, decreases with increasing LY. This results strictly in:

$$\mathrm{sgn}(\mathcal{J}(f)(x)) = \begin{pmatrix} 0 & 0 & 0 & + \\ 0 & 0 & 0 & 0 \\ - & + & - & - \\ + & ? & ? & - \end{pmatrix},$$

and in most reasonable cases:

$$\mathrm{sgn}(\mathcal{J}(f)(x)) = \begin{pmatrix} 0 & 0 & 0 & + \\ 0 & 0 & 0 & 0 \\ - & + & - & - \\ + & - & ? & - \end{pmatrix}.$$

3.3.4.2 Results

In the following, we will discuss the case where the last question mark is “–”, which is valid when agriculture contributes significantly to household income.

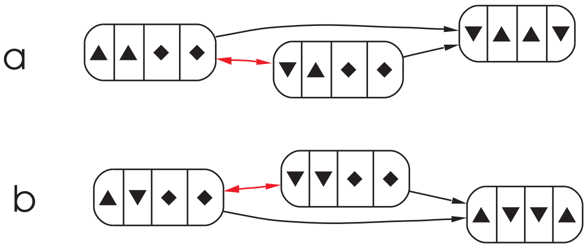

Figure 3.10. Resulting trajectories, sequence of variables as defined in the text (R, LT, LW, v).

In Fig. 3.10 the resulting qualitative trajectories are shown in their most aggregated form. We obtain two disconnected graphs, characterized by constantly increasing or decreasing total labor force, LT, which reflects that no feedback of the system dynamics on this variable was considered. In both cases a persistent trend combination occurs, the simplest form of an invariant set. In sub-graph (a) characterized by increasing LT, i.e. population growth, this set shows constantly decreasing resource quality, increasing engagement in off-farm labor and a decreasing fraction of the on-farm labor invested in sustaining or improving the resource. This means - according to the model assumptions - insufficient consumption per capita (below c_k). If an observed smallholder system shows this trend combination one cannot expect that the situation will improve due to the endogenous mechanisms. Further inspection of graph (a) reveals that this invariant set is a possible, but not a necessary outcome of the dynamics - an oscillatory behavior between states with increasing and decreasing resource quality is also in accordance with the model assumptions. A more detailed analysis of the result could probably identify dangerous trend combinations which could be precursors of the invariant set, such generating “early warning indicators”.

Sub-graph (b) is characterized by a decreasing population and here a desirable invariant set occurs: once in a situation with increasing resource quality, decreasing off-farm engagement and increasing labor investment into the resource base, the endogenous mechanisms will stabilize this trend combination.

In general these results emphasize the important role of the demographic development - only in case of decreasing population the considered smallholder system exhibits a stable and acceptable development path which is in this case based on the continuous improvement of the production system under control of the farmer. It should be stressed that decreasing LT means a decrease in labor force and a respective decrease in consumption. Population number reducing processes, like the disproportionate out-migration of younger people or those capable to work as well as the consequences of epidemics like AIDS do clearly not fulfill this condition.

3.4 From Competition to Cooperation in Sustainable Resource Management - A Multi-Actor Approach

So far syndromes have basically been analyzed as single actor problems. In a social environment the interaction among multiple actors can lead to many possible types of interaction, ranging from conflict among all actors (all couplings negative) to cooperation among all actors (all couplings positive). Game theory analyses a variety of archetypes of interactions, with the zero-sum game and the prisoner's dilemma game as well-known cases. These games play a role in natural resource management, in particular to understand the tragedy of the commons.

In the following, we describe the interaction between the reproduction of a natural resource stock R, the resource extraction (harvesting) E_i, profit P_i and the cost of extraction efforts C_i for actors $i = 1,\dots,n$ (cf. Scheffran 2000). The resource growth with extraction is represented by

$$\dot{R} = r(R) - \sum_i E_i,$$

which depends on the reproduction function $r(R)$ of the resource stock and the resource extraction by all actors, combined in the extraction vector $\mathrm{E} = (E_1,\dots,E_n)$. The extraction function $E_i = e_i(R, C_i) = \gamma_i R C_i$ for each actor i depends on the resource stock R, the extraction costs (investments) C_i and the extraction efficiency γ_i of the extraction technology employed. Resource reproduction is represented here by a logistic function $r(R) = rR(1 - R/R^+)$ where r is the reproduction rate and R^+ is the maximum carrying capacity of the ecosystem for R. Net profit $P_i = pE_i - C_i$ of actor i is the income from selling the extracted resource E_i on the market at price p, diminished by extraction cost C_i. According to the demand-supply relationship the price declines with extraction $D_{E_j} p = \partial p / \partial E_j < 0$. We use the standard linear function $p = a - b \sum_j E_j$ where a is the initial price for the extracted resource and b is the slope of the demand curve. Inserting the extraction function yields profit as a function of resource stock and extraction cost of all actors:

$$P_i = pE_i - C_i = \big(u_i - \sum_j v_{ij} C_j\big) C_i, \tag{3.16}$$

with market price $p = a - b \sum_j \gamma_j R C_j$, $u_i = a\gamma_i R - 1$, $v_{ij} = bR^2 \gamma_i \gamma_j$.

The dynamics of extraction cost is adjusted by a decision rule $\dot{C}_i = f_i(R, \mathbf{C})$ that describes an actor's response function $f_i : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}$ to the state of resources and current costs of all actors. An individual target setter would select a decision rule $f_i = k_i(C_i^* - C_i)$, moving towards a target cost $C_i^*(R, \mathbf{C})$ with response intensity k_i. Another decision rule describes an actor that adjusts cost proportionate to the gradient of profit with regard to cost change, $D_{C_i} P_i$, i.e. cost is increased or decreased proportionate to its impact on profit. $D_{C_i} P_i = 0$ is satisfied for

$$C_i = \frac{u_i - \sum_{j \neq i} v_{ij} C_j}{2 v_{ii}} =: C_i^*,$$

which will be used as target cost C_i^* of actor i following an optimizing decision rule. Then the dynamic interaction between actors and resources is fully described by the system of equations ($i = 1, ..., n$)

$$\begin{aligned}
\dot{R} &= rR(1 - R/R^{+}) - \sum_{i=1}^{n} \gamma_i R C_i =: g(R, \mathbf{C}) && (3.17)\\
\dot{C}_i &= k_i(C_i^{*} - C_i) =: f_i(R, \mathbf{C}) && (3.18)\\
P_i &= \big(a - b\sum_{j=1}^{n} \gamma_j R C_j\big)\gamma_i R C_i - C_i =: h_i(R, \mathbf{C}) && (3.19)
\end{aligned}$$

The couplings are given by the following set of inequalities. Here we use $C_\gamma = \sum_i \gamma_i C_i = \overline{\gamma} C$ as the total effective costs and $\overline{\gamma} = \sum_i \omega_i \gamma_i$ as the average extraction efficiency, weighted by the fractions $\omega_i = C_i/C$ of total costs $C = \sum_i C_i$.

$$\begin{aligned}
D_R g &= r(1 - 2R/R^{+}) - \sum_j \gamma_j C_j > 0 \ \text{ for } \ C < \frac{r(1 - 2R/R^{+})}{\overline{\gamma}} =: \tilde{C}^R,\\
D_{C_i} g &= -\gamma_i R < 0,\\
D_R f_i &= k_i \frac{1 - aR\gamma_i/2}{bR^3\gamma_i^3} > 0 \ \text{ for } \ R < \frac{2}{a\gamma_i} =: R_i^C,\\
D_{C_i} f_i &= -k_i < 0,\\
D_{C_j} f_i &= -k_i \gamma_j/(2\gamma_i) < 0,\\
D_R h_i &= \gamma_i C_i \big(a - 2bR\sum_j \gamma_j C_j\big) > 0 \ \text{ for } \ C < \frac{a}{2b\overline{\gamma}R} =: \tilde{C}^P,\\
D_{C_i} h_i &= u_i - \sum_j v_{ij} C_j - v_{ii} C_i > 0 \ \text{ for } \ C_i < \frac{u_i - \sum_{j \neq i} v_{ij} C_j}{2 v_{ii}} = C_i^{*},\\
D_{C_j} h_i &= -v_{ij} C_i < 0.
\end{aligned}$$

The signs are given in the following matrix, for $n+1$ input variables $(R, \mathbf{C})$ and $n+1$ output functions (g, f), where f is the respective vector of f_i. If the above equations are generalized to a model ensemble, e.g. to account for uncertainties in parameterizations, we obtain

$$\begin{aligned}
\mathcal{M} = \{&(g, f_1, \ldots, f_n)^t \in C^1(\mathbb{R}_+^{n+1}, \mathbb{R}_+^{n+1}) \mid \quad \forall i, j \in \{1, \ldots, n\}, (R, C_i, C_j)^t \in \mathbb{R}_+^3 :\\
&\qquad \operatorname{sgn}(\mathcal{J}(g, f_i, f_j)^t (R, C_i, C_j)^t) =\\
&\qquad\qquad \begin{pmatrix} \operatorname{sgn}(\tilde{C}^R - C) & \operatorname{sgn}(R_i^C - R) & \operatorname{sgn}(R_j^C - R)\\ - & - & -\\ - & - & - \end{pmatrix} \},
\end{aligned}$$

where the sign matrix is given blockwise to illustrate the basic interactions between two actors i and j the resource. They are depicted in the causal-loop diagram Fig. 3.11. What becomes clear is that the couplings of resources to resource growth $D_R g$ and to profit $D_R h_i$ are positive for sufficiently small costs $C < \tilde{C}^R$ and $C < \tilde{C}^P$. Both thresholds decline with resource stock R and average efficiency $\overline{\gamma}$. To find out which threshold is smaller we set $\tilde{C}^R > \tilde{C}^P$ and resolving the quadratic equation, we find $0 < R_1 < R < R_2 < R^{+}$ where the two limits R_1 and R_2 vary around $R^{+}/2$ with a range depending on $a/(2br)$. Thus for R in this middle range, an increase in costs first leads to a negative resource coupling to profit

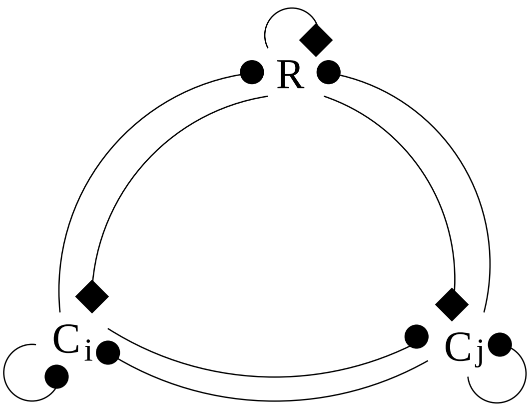

Figure 3.11. Part of the causal-loop diagram between the resource and two actors. Again arrows denote enforcing, bullets mitigating and boxes ambiguous influences.

and then to a negative coupling to resource growth. Closer to the resource boundaries the situation is the opposite. We study now two viability constraints (cf. also Chapter 2):

1. **Ecological viability:** The resource stock R is seen as viable if it exceeds a critical threshold R^-. $\dot{R} = 0$ leads to the equilibrium $\bar{R} = R^+(1 - C_\gamma/r)$ which corresponds to a sustainable total cost $C^{\mathrm{sus}} = r(1 - \bar{R}/R^+)/\bar{\gamma}$. Below the threshold $C^{\mathrm{ext}} = r/\bar{\gamma}$ there is no positive resource equilibrium $\bar{R}$. The resource stock is to stay in the sustainable domain $R^- < R \leq R^+$, where R^+ is the maximum carrying capacity for the resource stock R (upper limit) and R^- is a lower limit to keep a "safety distance" from total extinction. The growth rate adapts to this lower limit with the rule $\dot{R} \geq \alpha(R^- - R)$ which implies that resource growth should be positive as long as the resource stock is below the limit R^- and can be negative when resource stock is above the limit. The parameter α represents the required strength of adaptation. This ecological viability condition translates into a condition for actual change $\dot{R} = rR(1 - R/R^+) - \bar{\gamma}RC \geq \alpha(R^- - R)$. This leads to the ecologically maximal sustainable cost limit

$$C \leq \frac{r(1 - R/R^+) + \alpha(1 - R^-/R)}{\bar{\gamma}} =: C^R \tag{3.20}$$

which is positive for $R^- \leq R \leq R^+$ and may become negative outside of these limits. For $R \to R^-$ or $\alpha \to 0$, threshold C^R converges to $\tilde{C}^R$.

2. **Economic viability:** The flow of net profit for actors $i = 1, ..., n$ should exceed a threshold $P_i = pE_i - C_i \geq P_i^-$. The left-hand side is a quadratic function in both R and extraction costs C_i of actor i, depending on the extraction costs of all other actors C_j $(j \neq i)$. On the right hand side, the lower profit limit $P_i^- = K_i - K_i^-$ should guarantee that the available accumulated profit (stock of savings) K_i could exceed a lower limit K_i^-. This could be used for investing costs C_i. We discuss here the special case that these savings are at the lower limit $K_i = K_i^-$ which leads to $P_i^- = 0$. In this case, the equation above is reduced to $(a - b\bar{\gamma}CR)\gamma_i R - 1 \geq 0$ which generates the economic

viability condition for total cost of actor i'-s profit

$$C \le \frac{aR - 1/\gamma_i}{b\bar{\gamma}R^2} = \tilde{C}^p - \frac{1}{b\gamma_i R^2} =: C^{P_i}, \tag{3.21}$$

i.e. costs above C^{P_i} are too high to sustain minimal profits. Because of $C^{P_i} < \tilde{C}^P$, an increasing total cost will hit the economic non-viability thresholds of all actors before passing $\tilde{C}^P$ which implies that increasing resources reduce total profits: the smaller γ_i and the less efficient actor i is in extracting the resource, the tighter this constraint becomes. This confirms that the most efficient actors have the best chance to maintain profit in this competitive environment, suggesting that the most efficient actor can beat all others by further increasing extraction costs until its own limit is reached. The economic viability threshold becomes negative for $R < 1/(a\gamma_i)$, i.e. resource stock is too low for a given efficiency and initial market price. In other words, the efficiency $\gamma_i < 1/(aR) \equiv \gamma^*$ of actor i is too low to make a positive profit. This is the same efficiency threshold that all actors need to pass to make profit. Total joint profit of all actors becomes positive for

$$P = \sum_i P_i = (a - b\bar{\gamma}CR)\bar{\gamma}CR - C > 0.$$

which results in the upper cost limit

$$C < (a - \frac{1}{\bar{\gamma}R})\frac{1}{b\bar{\gamma}R} =: C^P \tag{3.22}$$

This cost limit becomes negative for $\bar{c} = 1/(\bar{\gamma}R) > a$ (which defines a resource limit R^P). $\bar{c}$ is the average cost for extracting one resource unit. Thus, this condition means that the unit cost exceeds the initial unit price of the resource.

Joint profit is maximized for $D_C P = 0$ which results in the optimal joint cost

$$C^* = \frac{a\bar{\gamma}R - 1}{2b(\bar{\gamma}R)^2}. \tag{3.23}$$

Inserting this into the profit function determines maximum profit

$$P_{max} = \frac{(a - \frac{1}{\bar{\gamma}R})^2}{2b} \ge 0.$$

Thus, if actors invest their joint optimal extraction costs, joint profit is never negative. However, this is generally not possible within the given boundaries, in particular for very small $\bar{\gamma}R$ which would require very high optimal costs which is not economically sustainable. On the other hand, very high $\bar{\gamma}R$ would not be ecologically sustainable.

Finally, we examine how total effective costs C_γ evolve, assuming $k_i \equiv k$ for all $i = 1,...,n$:

$$\begin{aligned} \dot{C}_\gamma &= \sum_i \gamma_i \dot{C}_i = \sum_i \gamma_i k_i (C_i^* - C_i) \\ &= k\frac{anR - \sum_i 1/\gamma_i}{2bR^2} - kC_\gamma \frac{n+1}{2} = k(\bar{C}_\gamma - C_\gamma), \end{aligned}$$

where

$$\bar{C}_\gamma = \frac{anR - \sum_i 1/\gamma_i}{(n+1)bR^2} \tag{3.24}$$

is the overall equilibrium. For $\gamma_i \equiv \gamma$ for all actors this provides the joint cost equilibrium $\bar{C} = \frac{(a\gamma R-1)n}{b\gamma^2R^2(n+1)}$ which is close to the zero-profit condition. $\bar{C}$ is negative for $\gamma R < 1/a$, reaches its maximum at $\gamma R = 2/a$ and then declines to zero for $\gamma R \to \infty$. For $n = 1$ we have $\bar{C} = C^*$, for large n we have $\bar{C} \to 2C^*$, i.e. individual optimization leads to an equilibrium far above the joint optimum.

So far we assessed the case of each actor acting according to its individual profits P_i, investment strategies C_i and extraction efficiencies γ_i and discussed their joint impacts on the resource stock which in return affects the joint profits and investments.

This situation can be assessed using viability concepts (for details cf. Chapter 2). The state space structure (see below for an example) cannot guarantee that every trajectory starting from a state which meets the ecological and the economic viability constraint will meet these requirements forever. In general, the viability kernel is a proper subset of the set described by the constraints. Thus, individual competition may lead to outcomes which are not ecologically or economically viable, or both, such that regulation and cooperation are relevant to stabilize the interaction within viable limits:

- One regulation strategy seeks to make resource extraction more costly, by substracting a tax τE_i from profit proportionate to extraction. This corresponds to replacing the initial unit cost by $a - \tau$ in all the equations above which implies that the cost thresholds and profit are reduced accordingly which allows for a higher resource equilibrium $\bar{R}$.
- As long as each actor seeks to adjust its extraction cost to maximize its own profit P_i, then the dynamics differ from seeking to maximize joint profit $P = \sum_i P_i$. To act jointly, the actors would match the joint decision rule $\dot{C} = k(C^* - C)$ by adapting their individual decision rules $\dot{C}_i = k_i(C_i^* - C_i)$, most obviously by selecting the response strength k_i properly. This requires mutual adaptation and negotiation on allocating joint cost, maximizing joint profit and distributing it to the actors according to criteria of fairness, e.g. proportionate to efficiency or efforts of actors.

A detailed assessment of such regulation measures is left to the future. We rather demonstrate here the general terminology for a specific case.

Example:
To specify the different threshold conditions, we use a particular parameter setting ($a = 1, b = 0.005, \bar{\gamma} = 0.005, r = 0.2, R^+ = 1000, R^- = 100, \alpha = 0.5, n = 6$). Note that it is not assumed that all actors are identical. However, the following results can be computed for the aggregate costs C. Figure 3.12 shows the two main isoclines C^{sus} for $\dot{R} = 0$ and $\bar{C}$ for $\dot{C} = 0$ as well as the directions of change outside of these curves. The various threshold curves defined in this chapter are depicted in Fig. 3.13 which shows the full complexity of the problem. Most striking is that at $R = R^P$ three of the four cost curves intersect. This implies that below this resource threshold positive profit is not feasible and that total costs $\bar{C}$ (individual optimization) and C^* (joint optimization) are negative which implies that there

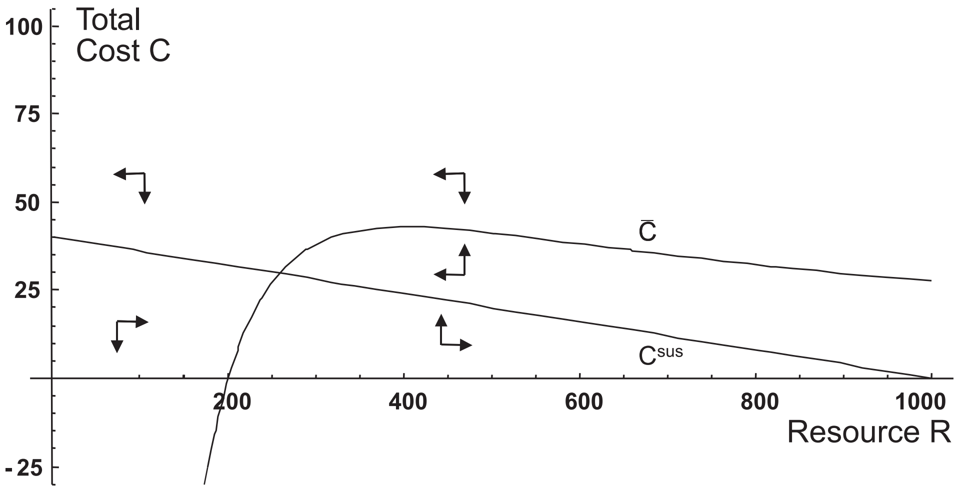

Figure 3.12. Special case for multi-actor resource competition in the cost-resource diagram, showing the main isoclines $\bar{C}$ for constant total costs and C^{sus} for constant resource stock. The arrows indicate the direction of the dynamics.

is no inventive to increase costs. The ecologically viable cost threshold C^R exceeds them all because the higher the resource stock the higher the admissible resource reduction and cost, as a function of R^- and α. As expected we have $C^R = C^{\mathrm{sus}}$ for $R = R^-$. The diagram also shows that for individual optimization the total costs $\bar{C}$ are about twice as high as for joint optimization C^*. We have $C^{\mathrm{sus}} > C^*$ for $R < R^C$ and else otherwise. It is also clear that the dynamics, given by the arrows, exceeds C^* which implies that the joint optimum is not stable against individual action (it is not a Nash equilibrium). For $C < \tilde{C}^R$ more resources spur resource growth until this threshold is exceeded and resource growth slows down to reach C^{sus} and resource growth stops.

3.5 Discussion

In this chapter we have shown how to deal with complex archetypal cause-effect patterns of global change. The derivation of the patterns (syndromes) already allows an improved awareness regarding the underlying problems, but also a structuring of information about complex situations. This is a precondition for anticipation of critical developments and any type of action useful to accomplish a turnaround to sustainability. The syndrome approach is a strong learning tool in this context, which can be applied to various stakeholder communities, raising awareness that improved conceptual and methodological concepts are needed to anticipate the development of the co-evolutionary dynamics of society-nature interactions. The detailed discussion in this chapter have made clear that such an analysis poses several challenges:

- Generality: models should provide insights for single applications, but should also apply to a broader set of cases with general features in common. They should classify and subsume different instances, because commonalities between different cases are

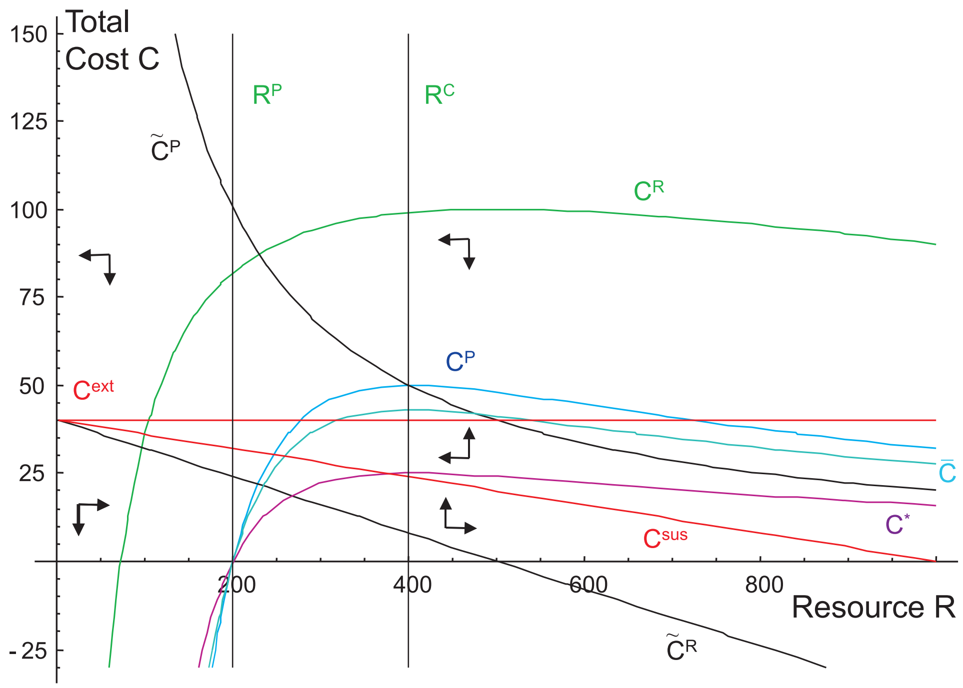

Figure 3.13. Special case for multi-actor resource competition in the cost-resource diagram, showing the thresholds for ecological viability C^R, economic viability C^P, change of couplings $\tilde{C}^R, \tilde{C}^P, R^C$, profit maximizing and equilibrium costs C^* and $\bar{C}$, and threshold costs C^{ext} and C^{sus}.

important to obtain a global overview, to classify different instances, and to be the base for transferring best practices.

- Uncertainty: models have to take account of various uncertainties. Many interactions of social-ecological systems are not known quantitatively, knowledge about the processes is often limited, there are data gaps or unpredictable future influences, e.g. depending on strategic political choice. Under such conditions, the modeler cannot discriminate between alternative quantitative models, but if urgency to solve a problem is high, the analysis and the management strategies should be robust.
- Quantitative and qualitative knowledge: to understand social-ecological systems, knowledge from different disciplines and with different degrees of quantification has to be integrated.
- Complexity: social-ecological systems tend to be composed of many tightly coupled, non-linear subsystems and interactions which are often difficult to disentangle. If this complexity cannot completely be resolved by models, adequate core mechanisms have to be identified.
- Normativity: it is necessary to classify patterns of interactions as problematic or desirable. This involves value judgments where science can only contribute. However,

> normative knowledge has to be considered in a transparent way and research can contribute to the assessment and development of management practices.

The discussed syndromes show that essential progress can be achieved which leads beyond the tradition syndrome analysis. This is feasible by utilizing smart mathematical methods from physics and information sciences. By applying this strategy a formal syndrome description is possible. Furthermore it might be reasonable that a general theory of complex man-nature interactions can be developed by application of the introduced concepts. QDEs allow to abstract from single cases whilst the viability concepts are suitable to test potential system developments against normative settings from policy or society (cf. Eisenack et al. 2006a for an example). This is important, since a lot of management strategies are put into action without a systematic analysis of potential side effects or potential failure factors. In this contribution we show how policy-relevant information can be deduced for complex problems even if we have only inhomogeneous knowledge on hand. For the Overexploitation syndrome, for instance, the most prominent result is the existence of boom-and-bust cycles. These make clear the urgent need to reconsider subsidies policies. Further several irreversibilities (no-return sets) allow to identify time horizons for concrete actions - otherwise safe limits cannot be achieved. Similar results are obtained for the Dust-Bowl syndrome implying that environmental impacts and sustainable productivity can only be guaranteed by an intelligent restructuring of regulations in industrial agriculture. For the Sahel syndrome it becomes obvious that smallholder’s pressure on marginal land can be reduced only by implementing a suitable population policy. It is further shown by a multi-actor approach that problems can be addressed adequately by combining game theoretic approaches with several other methods, as e.g. viability concepts and qualitative modeling. Our results causes the optimistic view that essential progress can be achieved and that therefore environmental systems analysis can surmount arbitrariness, in particular, if we are focussing on policy relevant information.

3.6 Conclusion

In this paper we introduced a mathematical and a substantial framework which allows to provide a systematic and cross-wide syndrome analysis. Archetypes are a suitable way of representing generalizable system features by reducing complex interaction to basic mechanisms. They cover a broad range of particular systems, i.e. a large class of uncertainties is considered at the same time. Furthermore they semi-formally represent qualitative knowledge. By operationalizing them as qualitative differential equations, also non-quantitative knowledge about trends and on ordinal scales can be included. Different normative assessments can be performed on this base using viability concepts. We further indicate ways to draw conclusions for the management of social-ecological systems.

We have shown how one can derive systems knowledge which lies far beyond the common practice to utilize short-term observations for long-term planning and management, although only weak systems knowledge is available. Although qualitative modeling and viability theory cannot provide exact quantitative predictions and crisp strategies, alternative development paths and feasible management options can be explored and implemented in the daily practice of decision makers (cf. syndrome related quotations in this Chapter).

Thus, the presented approach is not only a tutorial exercise, it paves the road to a closed theory-based analysis of complex man-environment interactions and for further innovative research.

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