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Models for the representation of ecological systems? The validity of experimental model systems and of dynamical simulation models as to the interaction with ecological systems

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A. INTRODUCTION, OVERVIEW AND OUTLOOK

1. Introduction

Life has been defined as ´things that make models´ (Patten et al., 1997) and models have been conceived as the only means for the acquisition of knowledge:"...alle Erkenntnis [ist] *Erkenntnis in Modellen und/oder durch Modelle*" (Stachowiak, 1983b, p. 129). Apparently, models are universal and indispensable. Models guide the observation, description and representation of and the interaction with ecological phenomena and systems. In this thesis the features and limitations as to representation and prediction of two model types, experimental model systems and simulation models and of the corresponding images of science are investigated.

To put this thesis into context the following paragraphs try to clarify the ´context of discovery´ and a few key terms such as ´model´ and ´sustainability´, to tentatively approximate the philosophy of science background and, finally, to present the scope and structure of the thesis.

When defining terms it should be kept in mind that definitions and theoretical concepts are essentially inseparable (Pawlowski, 1980) and that notions arise from an intricate interplay of conventions, empirical findings, hypothetical assumptions and criteria of simplicity and fruitfulness (Stegmüller, 1970).

1.1. ´Context of discovery´

The project "Sustainable production and utilisation of energy crops", framed this thesis. The initial mindset underlying the project was a positivist sender-receiver concept of causality and of human interaction with the ecosphere: Human activity causes matter, energy and eventually information fluxes into ecosystems which lead to observable and undesirable impacts. Environmental science was attributed the task of providing models for the representation of these interactions, for mitigation and for the "operationalisation of sustainability" (Härdtlein et al., 1998a, Härdtlein et al., 1998b, Lewandowski et al., 1999). Both ecosphere-anthroposphere and science-society were regarded as neatly separated, conceptually delimitable systems. This syntactic conception and the underlying paradigms are challenged in this thesis: Firstly, paradigms for the representation of ecosystems and the role of scientific models for knowledge production in the environmental sciences are critically reviewed. Secondly, in view of models´ limitations, images of ´science for sustainability´ (in the sense outlined below) are examined.

1.2. Models

There is a large variety of models in science, i.e. mental models (Paton, 1993), material model systems such as mesocosms, mathematical models ranging from statistical to functional and from phenomenological to causal models and simulation models (Wagner, 1997). Two types of models at the opposing ends of this range will be investigated in this thesis: (1)

Experimental model systems, which are related to the manipulation of material systems by laboratory practices. (2) Dynamical simulation models, which display a limited affinity to substance and to experimental practice.

A few words on the term ´model´ seem warranted at this stage. A general definition is: material or ideal (re-)production of an object by means of *analogies* realised by a cognitive subject (i.e. an observer) (Ehmke, 1997). Analogies are similarities among different objects concerning certain aspects or properties. They permit the inference of probable properties of object B from the properties of object A (Löther, 1997). Others, however, stress the function of models as *representations*, either ideal or real (Müller, 1983).

The referents of models are systems, or more precisely their structure (Weinert, 1995). Experimental model systems are dualistic in that they unite a material part with a conceptual or "structural" part. Simulation models, in contrast, consummate the tendency in physics (since Mach) to replace substance by structure (Müller, 1983); not the reflection of reality which is faithful to the object is regarded as true, but the *relation* which is faithful to the *structure* of a system. This iso- or homomorphism operates with mere symbols which need not correspond to elements of an objective reality (Jammer, 1965). The significance of models as a consistent synthesis of *a priori* independent elements of observation has increased ever since (Müller, 1983, p. 68). This synthesis usually has a mathematical and, consequently, fictional nature: "I think that a model - a specially prepared, usually fictional description of a system under study - is employed whenever a mathematical theory is applied to reality" (Cartwright, 1983, p. 158).

Models, theory and data are difficult to delimit. A model is always a simplified description of some features of a system (Joergensen et al., 1999) and models are more specific than theory in that they make use of a limited set of concrete parameters (Weinert, 1995) and in that they apply to a smaller range of phenomena (Wagner, 1997). Yet from a non-positivist point of view, data are theory-laden, while theory and models are functionally equivalent so that data and theory may be regarded as specific types of models.

Models have to be made. To construct a model, specific parameters have to be chosen and some functional or structural relationship between these parameters has to be expressed (Weinert, 1995). The neopragmatic modelling theory has emphasised the role of decisions and selections in modelling (Wernecke, 1994). Accordingly, models substitute an original for specific purposes and goals, for specific temporal intervals and for specific cognitive subjects (Stachowiak, 1983b), i.e. for specific observers.

1.3. Metaphors as background and analytical instruments as motor

Metaphors are the fabric of argument, analogical reasoning and model construction. Major sources of metaphors in ecology are physics (e.g., mechanical and systemic metaphors), the ´information´ sciences (e.g., computer, noise, memory, networks (Margaleff, 1991, Mikulecky, 1991) and more exotic areas such as medicine (ecosystem health; (Rapport, 1998, Rapport, 1995).

Metaphors convey a "surplus", i.e. they stand out from formal concepts, which are forced to reduction and abstraction (Blumenberg, 1998); thus they may inspire, but also stifle conceptual innovation. Take mechanistic metaphors which belong to the basic model of occidental science as an example . Their emergence is tied to the construction of mechanical clocks in early modern times (Merchant, 1987), which in turn stand for orderly and determinate behaviour (i.e. the world as a clockwork (Mayr, 1980). The pendulum visualises the orderly course of linear time and of processes taking place in time, and the pendulum remains a major point of metaphorical reference in discussions on dynamical models in biology and ecology; e.g. Bossel claims that so-called real-structure models "would be able to predict what would happen if the pendulum were stopped" (Bossel, 1992), while Kampis ascertains that new and a priori unpredictable variables of motion may come up any time (e.g. as the string of the pendulum breaks and the ball starts to roll (Kampis, 1994).

The development of analytical tools nourishes metaphorical notions. The discovery of complexity (Hedrich, 1994) has been associated with the advent of diverse analytical instruments such as computers, cybernetics and systems theory (Lilienfeld, 1978) and of self-organisation (Krohn et al., 1990, Paslack, 1991) which challenge linear and mechanistic metaphors and notions. These theories (arguably) claim universal validity (Lilienfeld, 1978) and hence could be regarded as interdisciplinary or "diagonal" theories (Heckhausen, 1987).

In the wake of this structural scientific revolution (Hedrich, 1994), talk of self-organisation has become customary in ecology (e.g., (Müller, 1996, Müller, 1997) ecosystems have come to be regarded as true systems (Trepl, 1988) and systemic and computational metaphors (Paton, 1996) have sprung up. Envisaging ecosystems as large computers presumably is linked to the rise of computers and simulation models. It seems as if the medium indeed was the message here (McLuhan) and as if any alternative to the computer metaphor was stricken with the drawback of appearing as a mere appendage to the computer metaphor (analogously: West and Travis, 1991).

1.4. Images of science: Representation for understanding and predicting?

The representation of ecological phenomena by models, one might be tempted to say, is guided by two major aims, understanding and prediction, just as the whole of science is (Toulmin, 1981). The spirit of the conventional separation of models into research tools (understanding) and predictive tools (see e.g.; (Huwe and Ploeg van der, 1992) seems to correspond to this image of science which represents, understands and predicts. Yet the terms prediction and understanding are far from being clear. For example it has been shown that prediction and understanding are not structurally equivalent and that the term prediction may adopt more than 30 different meanings (Stegmüller, 1969). Understanding may cover such divers things as an adequate conceptual representation or the capability of interacting successfully with a natural system. The term representation is as unclear. Representation may refer to mental states (and mental models), to substitution (of an original by a model) or to a relation between signs which conserves the structure of the represented original (Scheerer, 1993). Hence both the mental models which guide a farmer and the scientific models which conserve the structure of the original are representations.

I claim that a positivist image of science, which aims at the understanding of well-defined, disciplinary mini-problems, "puzzles" (Kuhn, 1970) and at the prediction of controlled and shielded laboratory systems is misleading, particularly in the environmental sciences: On the one hand it may overrate the contribution of science and its models to the understanding and predicting of *real-world* systems (as opposed to the manipulated, abstracted systems of laboratory and theory) and on the other hand it may underrate the potential for the interactive organisation of ecological knowledge and for the (re-)contextualisation of knowledge in local applications.

1.5. Images of science for sustainability

The positivist image of science according to which science follows its internal logic to continuously approximate an objective reality and produces universal, objective knowledge has been challenged recently by science research (Felt et al., 1995), but also by environmental "science in action" (Latour, 1994). Risk assessment, for example, the concept of sustainability or the precautionary principle have challenged the positivist image (Funtowicz and Ravetz, 1993b, Hansson, 1999, Nowotny, 1993, O'Riordan and Jordan, 1995, Röling and Jiggins, 1994, Rosa, 1998). I subsume environmental issues which do not fit into the positivist puzzle framework under the term ´sustainability issues´ and try to clarify the notion of sustainability underlying this thesis in the following.

Sustainability has been called the last great narrative of modernity (Fischer-Kowalski and Schandl, 1998: "Sustainable Development als gegenwärtig letzte ´große Erzählung´), left after other narratives such as "progress" had to step back and give way to post-modern arbitrariness. A concept of sustainability should acknowledge that a global exo-perspective has been lost and that mankind does not stand outside nature, to manipulate and control it, but that the environment, its state and its evaluation are constructed within society (Nowotny, 1996).

Sustainability faces ill-defined issues (Scholz, 1997) and soft systems (Checkland and Scholes, 1996), for which neither the means nor the ends/goals are clear. ´Hard´ system descriptions, i.e. abstracted and formalised descriptions can offer no substitute for the process of deliberation in which observers and actors frame systems and negotiate goals for concrete systems. Thus perspectivity, values and norms become mingled with ´facts´.

Sustainability necessitates management instead of solutions and schemes of practical interaction with concrete systems instead of objective and universal representations. Universal and context-independent representations can not compensate the lack of experience with the corporeal world[1]. As to the time dimension, the concept of sustainability suggests to keep the future open for certain developments (Nowotny, 1996): While I agree that in principle the

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[1] Experience plays a ever smaller role in the world we live in, becoming replaced by the universalized expectations produced by scientific specialists to whom the world is an object of possible or potential experience (Marquard, 1994)

future has, topologically spoken, an open, bifurcated structure (Wright, 1994), its degrees of freedom are ever more restricted by the "extended present" we live in (Nowotny, 1995, p. 52-53).

To summarise, I contest that sustainability is a hard, operationalizable concept, which could be defined naturalistically as others suggest (e.g., Härdtlein *et al.*, 1998a). I argue in favour of its irremediably discursive character, which calls for negotiation and context-dependent (´local´) definitions instead of reductionist, naturalistic and universal formulations.

1.6. Scope and structure of the thesis

The thesis consists of seven parts, this introductory section (A) and six papers (B-G; fig. A.1).

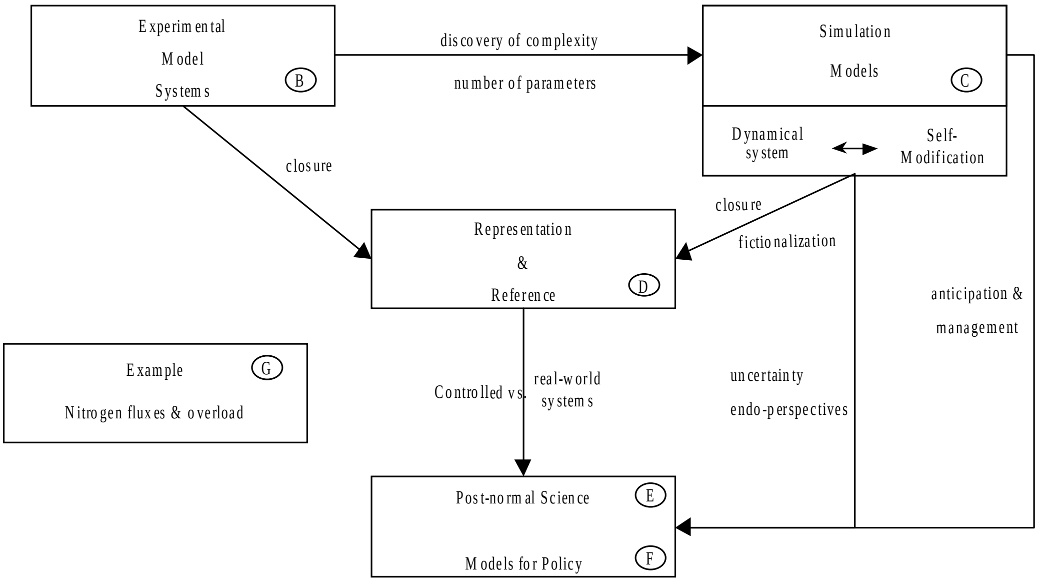

Figure. A.1. Scope and structure of the thesis and the interrelation of the papers.

Paper B investigates experimental model systems; in particular, closure and the establishment of control are addressed and it is discussed how model systems relate to their reference, the ecosystem. In contrast to experimental model systems, theories of the complex such as the theory of dynamical system facilitate the simultaneous handling of a much larger number of parameters (fig. A.1.). Paper C critically revises dynamical simulation models, opposing the paradigm of the dynamical system (with its notion of an abstract state) and the paradigm of self-modifying systems. It is claimed that the scheme for closure and control in the laboratory serves as a model for the closure of dynamical models. Paper D argues that simulation models suffer from a diminished contact to their reference, the ecosystem ("fictionalisation"), and it compares the (contrasting) ways, how model and original are re-related in technoscience (due to the extension of the laboratory conditions) and in simulation modelling (fitting of the model to the data). Papers E and F take up the limitations of simulation models and it is outlined how uncertainty[2], unpredictability and the notions of self-modification and endoperspective could affect the image of science and the role of models for decision-making and management. Paper F elaborates on the role of models for policy, embedding modelling into a post-normal conception of a managerial science for policy. Paper G presents an example, the emission of excess nitrogen from agriculture which contributes to a "post-normal" issue, global N overload (characterised e.g., by large scale, scope, stakes and epistemic uncertainty); the suitability and validity of different model (among them simulation models) and remediation approaches are discussed.

2. Material

The material for this theoretical thesis was extracted from a wide range of scientific papers and books. In the following I roughly sketch the different areas considered and give a few examples of representative authors for illustration in a footnote[3]:

(a) empirical work from the environmental sciences represented mostly in the review paper on nitrate fate (see G.)
(b) contributions to ecosystem theory and to modelling in the environmental sciences, ranging from hierarchy theory and the matter/energy/thermodynamics school to advocates of an information paradigm for ecosystem research.
(c) conceptual and philosophical work on models and their role for the environmental sciences (with a focus on the issue of validity and validation and for knowledge acquisition in general.
(d) philosophical work on the role and uses of experiment.

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[2] I use the term uncertainty as a generic one; a more precise terminology would distinguish risk, uncertainty (unknown probabilities, but known possible outcomes) and indeterminacy (unknown probabilities; unknown outcomes) (Scheringer, 1999). In many instances in this thesis uncertainty refers to the indeterminacy inherent in ecosystems.

[3] Hierarchy theory: Ahl and Allen, 1996, Allen and Hoekstra, 1992, O´Neill et al., 1986; system ecology with a matter/energy paradigm Joergensen, 1992, Joergensen et al., 1995, Müller, 1997. Information paradigm: Hauhs and Lange, 1996a, Hauhs and Lange, 1996b, Lange, 1999, Lange et al., 1997

models: Wagner, 1997, Weinert, 1995. Validity: Funtowicz and Ravetz, 1992, Konikow and Bredehoeft, 1992, Oreskes, in press, Oreskes et al., 1994, Rastetter, 1996, Rykiel, 1996. General modelling theory: Stachowiak, 1973, Stachowiak, 1983a, Wernecke, 1994

Role and uses of experiment: Gooding et al., 1989, Hoyningen-Huene, 1989, Latour, 1990, Le Grand, 1990, Pickering, 1989, Pickering, 1990, Radder, 1986, Rheinberger, 1995

Science research: Felt *et al.*, 1995, Knorr-Cetina, 1991, Latour, 1994, Latour and Woolgar, 1979, Nowotny, 1997, Nowotny, 1999a, Nowotny, 1999b

Risk : Hansson, 1999, Kolek, 1993, Kunreuther and Slowic, 1996, Renn, 1998, Rosa, 1998, Stern and Fineberg, 1996b, Stern and Fineberg, 1996a. Precautionary principle: Martin, 1997, O'Riordan and Jordan, 1995, Perrings, 1991, Sandin, 1999, Westra, 1997. Post-normal science: Funtowicz and Ravetz, 1993a, Funtowicz and Ravetz, 1993b, Funtowicz and Ravetz, 1991. Managerial science: Nowotny, 1993

(e) contributions from the sociology of science (Luhmann, 1994) and from science research critically investigating "science in action" scientific practices and different forms of knowledge production.

(f) work from an emerging (transdiscplinary?) field where the environmental sciences become interlocked with philosophical, sociological and normative deliberations; characteristic topics are risk, the precautionary principle, the notion of post-normal science and of managerial science.

The thesis aims at the interdisciplinary integration of the different perspectives and pretends to be a tentative contribution to a reflective theory of ecology and the environmental sciences.

3. Results, threads and themes

A few recurrent themes and threads will be outlined in the following to account for linkages and common backgrounds of the different papers.

3.1. Modelling as encoding

Modelling can be envisaged as an encoding process, in which natural phenomena and process are ´translated´ into parameters and (mathematical) relations, i.e. the natural system is encoded into the propositions of a formal system representing the (abstract) state of the system. Inferences on the behaviour of the formal system (e.g., a dynamical system), are then decoded to the natural system to produce statements on its behaviour (Rosen, 1991). Encoding in models is faced with a frame problem (Paton, 1996), i.e. the question which variables are adequate to represent an ecological system (Kampis, 1992a). Encoding is at the root of both experimental model systems (B) and of simulation models (C, D).

Abstract states

The Greek philosophers Parmenides and Heraklit first uttered the dichotomy of being versus becoming. According to Parmenides, the world is unchangeable and time reversible, while Heraklit claims that the world is subject to constant change and time is irreversible (Mainzer, 1995). ´Being´ by way of historical accident (Longo, 1994) still dominates Western thinking and static notions, self-identity and the assumption of identity in time belong to the fable of modern science (Merchant, 1987, pp. 232).

The notion of an (abstract) state captured by a set of parameters/variables and their relation, reflects this tradition (C). Eco-Systems frequently are equated with state variables which are interrelated through the processes (formalised as mathematical relations) while the processes are interrelated through the state variables (Joergensen *et al.*, 1999). The abstract state can be updated by applying a temporal transition function. The variables define a state space in which the ecosystem moves along trajectories computed by the formal system. The state space model (Patten *et al.*, 1997) asserts that there exists one and only one sequence of inputs that, starting from an initial condition, will put an open system in a given state (Joergensen *et al.*, 1999). The state-space conception corresponds to the image of Wittgenstein´ Tractatus world: the state of the world at a given moment can be characterised entirely by indicating which elementary, logically independent states exist (Wright, 1994). Time in this conception is external to the phenomena, universal (Mittelstaedt, 1980) and homogeneous; it has no privileged points such as the now and no beginning nor end (Rescher and Urquhart, 1994) and it can be treated as an external parameter.

Contingency

The identification of abstract states is in line with a long-standing programme in philosophy and then science[4] to reduce and eventually eliminate contingency. In C and D we show that dynamical models follow this rationale in that they aim at the abstraction of the dynamical part of a system from its contingent features, which are relegated to initial conditions, free parameters and ´background/noise´. The dynamical part is frequently taken to stand for the identity of the natural system and is equated with the essence of this system.

The recent programmatic shift from ´being to becoming´ (Prigogine, 1988) or from linearity to history via complexity (Longo, 1994), which puts supposed contingency into a different light, is one guideline of this thesis.

Encoding as framing mediated by language

Conventionally, encoding is assumed to follow a sender-receiver conception (Janich, 1992a), in which nature under investigation[5] sends syntactic and objectiveable signals to scientific observers concerning her being. However, I agree with the work of others who claim that distinctions (Luhmann, 1994), selections (Knorr-Cetina, 1991) or decisions (Stachowiak, 1973) form the basis of observation and of modelling (F). This may be in the form of laboratory selections for model systems, e.g., the selection of certain materials, instruments and experimental set-ups or in the form of decisions, e.g., decisions as to which variables and processes are relevant for a simulation model. Established sets of specific distinctions, selections and decisions form a perspective and may be characteristic for certain disciplines (i.e. scientific subsystems) or other, cognitive, or social systems. The validity of perspectives and reading frames is a matter of intra-, interdisciplinary or even transscientific validation, depending on the respective issue and the relevant social (sub-)system demanding the justification of knowledge claims.

Adopting the shift from the Tractatus world to the linguistic turn (Wittgenstein, 1971), I agree with the idea that reality is irremediably mediated by language and that facts, statements and hence natural states are necessarily framed by language (Janich, 1992a, Janich, 1998) and not

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[4] Hegel writes:"Die philosophische Betrachtung hat keine andere Absicht, als das Zufällige (i.e. das Kontingente; D.H.) zu entfernen. " (cf. (Marquard, 1987). And as to the role of contingency in science it may be said: "Zu jedem Zeitpunkt war die Physik strukturell eingeteilt in zwei grundsätzlich verschiedene Teile: in den dynamischen und in den kontingenten. Zu jedem Zeitpunkt konnte man einen bestimmten Teil der Phänomene durch Gesetze erklären, und der andere Teil blieb einfach übrig als Anfangsbedingung oder freier Parameter." (Kanitscheider, 1999).

[5] Note that Bacon´s "experimental account", which became the model of experimentation was apparently inspired by early modern torture of witches (Merchant, 1987).

by an objective, underlying world to which language corresponds (as a correspondence theory of truth world suggest (Hempel, 1992).

3.2. Ecosystems as open systems

When addressing the relation between model and original one touches on issues such as prediction and reference (see below) and on a variety of terms such as equivalence, adequacy, congruence and correspondence; representation and substitution; relation, transformation and code; correlate and copy; concretion, abstraction, realisation, interpretation and formalisation; verification, validation, confirmation, corroboration and evidence (Müller, 1983). Prerequisite for addressing these issues is a conception of the original, here the ecosystem, which is to be set against the model, i.e. the assumptions and analogies, which experimental model systems (B) and dynamical simulation models (C-F) invoke. Hence in the following I outline the notion of the ecosystem underlying this thesis[6].

Without physical openness or object openness (Joergensen *et al*., 1999), encompassing material, energetic, thermodynamic and informational openness, no organism and no ecosystem could exist. For example, energy input is necessary for anti-entropic, exergetic processes, cycling processes and emergent properties; net outflow of entropy is a basic condition for existence (Joergensen *et al*., 1999).

On-line systems with rule-making capacities

Receiving external inputs (whether natural or anthropogenic) ecosystems are subject to ´disturbance´ and become instationary; instationarity, however, has also endogenous sources (the distinction of the three sources of instationarity is drawn from (Lange, 2000): Ecosystems can be considered selfmodifying systems, i.e. component system which draw upon an open-ended set of different types of components, which produce and destroy their own components during their typical activities (Kampis, 1992b) and which produce internal novelty on-line[7]. It usually may be legitimate to take physical and chemical systems off-line for the purpose of computation as during computation these systems do not modify the rules according to which they behave (Fuchs and Hofkirchner, submitted). Ecosystems, cognitive systems and social systems, however, continue to evolve. In contrast to non-living systems, in ecosystems actors, agents of evolutionary change exist, which according to the evolutionary contingency thesis have rule-making capacities (Beatty, 1995). Physical-chemical laws only stake out a space of possibles, yet the degrees of freedom for behaviour and rule-change remain large. Accordingly, "there may be genuine laws that are relevant to biology, (e.g., laws of physics and chemistry), but those laws are not distinctively biological" (Beatty, 1995, p. 75).

When an on-line system is treated as an off-line system for analytical purposes, for example when ecosystems are encoded as dynamical systems, the ecosystem is converted into a stable

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[6] This conception of the ecosystem can in turn be regarded as a model, though a semantic, fragmentary, conceptually open and partly metaphorical model, which is neither formalized nor materialized.

[7] The debate on which codfication is appropriate might be pointless, in case ecosystem behavior can, analogously to human behaviour, not be codified, formalized and reduced to a set of rules *at all* (Woolgar, 1987).

system of stable signs (more on encoding and conceptual and material stabilisation in C, D). Yet converting the living into stable signs has a price: The only way of converting a human being into a stable sign is to kill her (Gendolla, 2000); the same, I would argue, holds for ecosystems.

In many physical-technical systems, the situation is somewhat different. As the setting of e.g. astronomical systems is rather stable on human time scales it is possible to accumulatively build a closed (for closure see below) model of the relevant system and simulate specific human interaction with that system: "What is admirable is.. how the complete space flight can be simulated in advance, and then slowly extended..., by incorporating *inside* the Space Centre more and more *outside* features brought back to the centre by each trial. " (Latour, 1994, p. 248)[8]. For ecosystems, such a step by step incorporation easily fails, as the representational knowledge brought back from a concrete ecosystem is likely to be invalidated due to self-modification.

Microdetermination versus emergence

For many physical and chemical systems, microdetermination (Klee, 1984) is invoked (see B), claiming that at the system level there are not degrees of freedom (Hoyeningen-Huene, 1994) and that consequently reductive experimental and explanatory approaches are justified (B). Yet microdetermination may not hold for living systems such as cognitive systems or ecosystems. Ecosystems may be regarded as hierarchical (Ahl and Allen, 1996, Allen and Hoekstra, 1992, Müller, 1992, O´Neill *et al*., 1986), self-organising systems, in which unpredictable (and incomputable?) system level properties and constraints emerge from the interaction of subsystems (Joergensen et al., 1992, Müller, 1996). Yet one may object that emergentism suggests that "macro-properties ... come out of nowhere. But why? ... They have been here in the world all along, standing right beside the properties of microphysics."(Cartwright, 1999, p. 33). In any case, whether emergent or not, little is known about the existence and character of ecosystem level laws.

The generation of meaning

The view of ecological systems as stable ensembles of syntactic signs (D), which can be represented objectively by a purely syntactic model (equating syntactic with objective as has been common since Netwon (Rosen, 1991) contrasts with the context-relativity of the meaning of the signs. The syntactic information supposedly encoded in ecosystem components are insufficient to deduce the corporeal appearance of the ecosystem and its phenomenology. Take the syntactic information in the genetic data of an organism: "The context of an ecosystem assigns meaning to the biological data set encoded in the genes, i.e. it provides the machinery by which it can be expressed into organisms. No procedure is known by which this assignment of meaning can be atomized, it seems to reside in the context as a whole" (Hauhs and Lange, 1996a).

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[8] Yet even here the logic of the situation which recurrs fails to capture the details which make a particular situation unique, as Challenger tragically demonstrated (Checkland and Scholes, 1996).

I would conjecture that ecology could benefit from a conception of information that is not limited to syntactic, naturalist perspectives (e.g., Janich, 1992b, Janich, 1996b, Janich, 1998).

Summarising it may be said that ecosystems contradict static notions and the assumption of identity in time (see above). Ecosystems are epistemically (Joergensen *et al*., 1999) or conceptually (Kampis, 1994) open systems, which change rules and setting endogenously.

3.3. Experimental model systems

Following a reductionist rationale, ecosystems are compartmentalised and studied under manipulated conditions, allowing for the investigation of a limited number of parameters and for the inference of causal relationships and the causal capacities (Cartwright, 1994) of the investigated parameters. In B we build a picture of prepared experimental set-ups as models for ecological phenomena and systems, i.e. as model systems and we highlight the underlying assumptions and the limitations of this model conception:

Experimental model systems are closed systems; they are spatially and temporally bounded and conceptually closed as matter, energy and information flux into and from the system are supposedly controlled by the experimenter.

Model systems are dualistic as along with a conceptual model component they consist of a material component which has to be manipulated and closed and which is encoded into a formal, numerical-mathematical system measuring certain parameters. Each measurement highlights certain features of a system and assigns them quantitative values, relegating all other features to the background (i.e. the unmarked space; F).

We distinguish different types of set-ups and model systems, based on their characteristic duration, spatial heterogeneity, number of factors and control of boundary fluxes as related to closure and control of the model system.

Analogy assumptions and decoding

Scientists use experimental systems as models of ecosystems based on the assumption that analogies between the model system and the ecosystem exist (examples of such analogies are "representative" samples, mesocosms or the substitution of adult by juvenile organisms) and that the two material systems realise a common formal system. Accordingly, three steps to infer statements on ecosystem behaviour from experiments can be distinguished: (1) establishment of an analogy between experimental system and ecosystem, (2) encoding of the experimental system into a formal system and (3) decoding to the ecosystem and inference of statements on the ecosystem.

The analogy assumption and the decoding step, however, face a radical discrepancy between the concept and realisation of model systems and eco-systems. Model systems are materially/physically and conceptually closed and idealised systems, which are arbitrarily bounded in space and time. They comprise a limited number of a priori defined factors arranged in a stable setting and shielded from environmental influences (see the notion of a "nomological machine" (Cartwright, 1999); adapted to ecology in D). Model systems result in abstract, formal process and system descriptions, entailing little for concrete, real-world systems. Ecosystems, in contrast are physically (e.g., thermodynamical openness, broad range of external influences) and conceptually open systems due to non-linearity and sensitivity to initial conditions, to feedback loops and indirect effects, to historicity and long-range correlations, to the emergence of system level properties and constraints and, maybe most importantly, due to the on-line production of internal novelty (Kampis, 1994; for more details see C).

In D we conclude that conducting experiments it is possible to identify causal factors. Ecosystems are open systems with an unstable, instationary setting and with infinite factors interrelated in changeable ways. These factors may enhance, reduce or neutralise the effect of an experimentally determined factor. Experimental model systems thus need to be evaluated: How does the generalised model system relate to a concrete system with a concrete history in a concrete location?

Model systems and the phenomena observed through the agency of these systems are created by scientific observers (Latour, 1994, Rheinberger, 1995); see also below on reference), conforming to the verum factum principle of modern science which states that truth and understanding can only be attributed to systems constructed by man (Hösle, 1990). Model systems correspond to one of the states of nature Bacon distinguishes, the state of slavery or techné (Merchant, 1987, p. 181): due to the craftsmanship of the experimenter nature is subjugated and controlled by way of artificial, ´technical´setups[9].

3.4. Dynamical simulation models

Theories of the complex such as systems theory and the advent of computers made it possible to simultaneously handle a much larger number of parameters than in experimental model systems, presumably in a controllable and tractable way. A parameter is here conceived as an objective-real entity or factor, which influences a given material phenomenon causing concrete effects (Franz, 1997).

Dynamical systems have since become *the* paradigm for the representation of ecosystems (Lange, 1998). "A dynamical system is one whose state changes with time (t)" (Arrowsmith and Place, 1994). Dynamical systems are conceptually closed systems in that they consist of a set of *a priori* fixed and specifically related variables, which define an abstract state (Kampis, 1994); the state of the system is updated with the help of the external parameter time. Accordingly, the ´behaviour´ of an ecological system can be computed and, assuming certain values or developments for external driving factors, scenarios and future states can be simulated. Dynamical simulation models of complex ecological systems and so-called integrated models of e.g., economic-ecological systems (Costanza et al., 1993) are used both in research and science for policy.

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[9] Natura naturans, the opposing (Aristotelian) state, comes closer to our notion of natural ecological systems, which change their setting in a self-modifying way.

Simulation: From simulating diseases to the simulation of systems

The notion of simulation has an agitated history. Originally referring to the simulation of an illness it nowadays refers to the representation of physical, biological, ecological etc. processes through mathematical or physical models, allowing for a realistic though *simpler, cheaper or less dangerous* investigation than the studied object itself (Brockhaus-Enzyklopädie, 1983). The medium computer and computer simulations offer the advantage of *reducing* contact to the original/reference and of protecting the human observer from excessive contact with reality. However, in D it is illustrated that simulation may reduce contact to reality to such a degree that its signs start forming a closed self-referential system (Baudrillard, 1982).

Based on the notion of self-modifying systems in C we criticise this essentialist notion, which bans contingency from the model following a laboratory conception of closure. Yet it fails, of course, in banning contingency from the represented system, which in the course of time tends to diverge more and more from the static representation of the model. Thus the model is exposed to the danger of losing contact to the original and the predictive capacity of models becomes limited (C).

3.5. Closure and stability

Stability is a prerequisite for the successful representation, prediction, management and intervention into systems. Stability is a complex (metaphorical) concept, encompassing and interrelating so divers aspects as material stability or the stability of the object under study, laboratory stability achieved through purification, conceptual stability, technical stabilisation when the objects of the laboratory are reproduced outside the laboratory, and real world or pragmatic/social stability through the establishment of an technology and a network of actors. In the following I try to shed a light on the different facets of stability that recur in the different parts of this thesis.

Stable settings

The stability of a system may be equated with the stability of its structure (see the definitions of ´model´ above) or, more general, of the setting. "What a system does depends on the setting, and the kinds of settings necessary for it to produce systematic and predictable results are very exceptional" (Cartwright, 1999, p. 73). Stability is rarely found, usually it has to be created some way. Material and conceptual purification in experiment and theory is an established scheme for stabilisation (B), avoiding contact with messy real-world systems. Accordingly, "physical systems ... are highly abstracted and idealised replicas of phenomena, being characterizations of how the phenomena *would have* behaved *had* idealised conditions been met" (Weinert, 1995). When scientists build model systems they pursue this rationale, building nomological machines (Cartwright, 1999); see D), i.e. stable settings which are shielded from the (messy) environment and in which different components with specific capacities are interrelated in a known way (see the hint at the machine metaphor and at the verum factum principle above). Stabilisation and shielding aims at the material and conceptual closure and control of the system, as we argue in B. Closure, however, is *relative* to the domain of phenomena of interest, to the respective theory (Radder, 1986) and to the list of parameters/factors selected as relevant for the representation of the phenomena. Hence differences, selections and decisions come into play again.

In C we argue that this laboratory conception of closure and control may be regarded as a ´model´ (in the sense of a standard to be imitated) for dynamical modelling in that dynamical systems aim at the exclusion of contingency or ´noise´ and at a high degree of closure. Moreover, they make use of descriptions, parameter values, laws etc. obtained under lab conditions. Yet, when applying dynamical models to non-laboratory conditions, the setting is beyond control, the shield has to be removed and the system opened, so that contingency enters and the laboratory account may not obtain.

Extending closure

There is more to stability than just the material and conceptual closure of an experimental set-up. While stability depends on how the world is, it also depends on skills, instruments, theories and the mutually reinforcing judgements of other scientists about all three (Gooding *et al*., 1989, p. 14). There is a process of self-vindication; "as a laboratory science matures, it develops a body of types of theory and types of apparatus and types of analysis that are mutually adjusted to each other", (Hacking, 1992, p. 30); they become a "closed system"[10]. It would be interesting to investigate the role of simulation models in this self-vindicating network.

To function outside the laboratory, theory and world have to be tailored to each other (Hacking, 1992), the laboratory conditions have to be extended: "Every time a fact is verified and a machine runs, it means that the lab .. conditions have been extended in some way" (Latour, 1994, p. 250). This extension is not restricted to the technical, it requires the stabilisation of a larger network of actors; e.g., "**negotiation** between Pasteur and the farmers´ representatives" was necessary "to transform the farm into a laboratory" (Latour, 1994, p. 249; my emphasis). For successful stabilisation and closure the social setting needs to be stabilised (Radder, 1986), else the predictions fail pitifully and the system is sent back to the laboratory (Latour, 1994). Utilisation technologies such as forestry (Hauhs, 1999, Hauhs and Lange, 2000b, Hauhs et al., submitted) or agriculture stand for the successful extension of the network, which e.g., stabilises the natural setting through regular reset and the socio-technical setting through the training of future users by an established educational system.

Apparently, both on the object and subject side a number of conditions is necessary for successful stabilisation, closure, and prediction, which here in effect is a "*retro-diction*" (Latour, 1994, p. 249), as the setting is to be stabilised *ahead of* prediction. In contrast to many areas of technoscience, the contribution of ecological models to extension, stabilisation and retro-diction is frequently limited. The lacking reference of both experimental model

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[10] Heisenberg called Newtonian mechanics "a closed system" that is essentially irrefutable (Hacking, 1992).

systems (see above) and simulation models (D) to ecological systems and the impossibility of employing these models as blueprints for the moulding and stabilising of ecosystems may be one reason why for example foresters disregard science as a source of knowledge for the improvement of their technological systems (Hauhs, 1999).

3.6. Reference and representation as creation

It might be claimed that contact and reference to reality are progressively lost along a line from mimesis via representation to simulation. While experimental model systems would stand somewhere in between mimesis and representation[11], simulation models would belong to the final stage of an also historical development, in which signs progressively lose an assignable meaning and reference to the objects of reality (Baudrillard, 1982). However, for any representation and any model, whether an experimental model system or a simulation model it is easy to state that representations correspond to things, processes or relationships, but it is notoriously difficult to justify (Gooding *et al.*, 1989, p. 14). For in experimental systems scientific objects are "...articulated from traces, or graphemes, within a space of representation. Outside such a space, the particular piece of nature set up in the laboratory remains without scientifically assignable meaning" (Rheinberger, 1995). The phenomena are thoroughly constituted by the material setting of the laboratory (Latour, 1994); representation thus is equivalent to bringing scientific objects into existence (Rheinberger, 1995). Not only simulation models, but also experimental model systems suffer from lacking contact to the outside world: "Nature as such, then, is not a reference point for the experiment, it is even a danger ...the reference point of any experimentally controlled system can be nothing else but another experimentally controlled system " (Rheinberger, 1995). Reference has to be created ex post, by extending the laboratory conditions into the real world (see above, closure).

Simulation models neither bring their objects into existence nor are they suitable for the transformation of the setting of the real world. The representation function of simulation models should thus in my view not be overrated.

3.7. Modelling for policy

Simulation models frequently are employed outside the realm of academic, normal science, e.g., in decision-making, risk assessment and regulatory issues. In F we discuss the framing and encoding of ecosystems in the context of science for policy. We argue that conventional frames such as the dynamical system follow an essentialist rationale entailing two major shortcomings: Firstly, they are incapable of handling internal novelty production which in the course of time invalidates the closed frame of description (see C). Secondly, the implicit assumption that the essence of the system can be captured contrasts with the descriptive complexity of such eco- or integrated systems, for which competing non-equivalent descriptions are derived from different exo- and endoperspectives and rationalities. Based on a constructive notion of observation, we show that the different descriptions are relative to the

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[11] Experiments which imitate nature by images or models have a long history. Wilson, for example, followed a mimetic approach in his cloud experiments (Gooding *et al.*, 1989).

domain of phenomena of interest, the differences and selections applied to the system, to the choice of variables etc. As uncertainty as to the behaviour of self-modifying systems increases, descriptions become ever more dependent upon interests, values and norms, resulting in a plurality of legitimate descriptions and in epistemic uncertainty. Scientific knowledge claims need not no longer be justified only within the confines of a small peer community, but are subject to public contestation.

Epistemic uncertainty as to ´complex´, ill-defined problems can not be remedied by the puzzle solving activity of normal science; while scientific inputs are irremediably soft, decisions to be taken are hard. For such issues a managerial, post-normal type of science has been conceived, which accounts for the plurality of non-equivalent descriptions. According to this concept, discourse among stakeholders and deliberation are needed to identify phenomena and parameters of interest, to formulate problems and to frame observation and analysis. Science would have to abandon its privileged epistemic standpoint, participate in discourse with stakeholders (extension of the peer community, democratisation) and become one societal subsystem among others, contributing to the social construction of observational frames and to the integration of different perspectives and knowledge types.

3.8. Prediction or space of possibles?

To Aristotle, prediction was a fictional endeavour, i.e. the task of poets reporting what could happen and *what would be possible* according to necessity or adequacy (Gendolla, 2000). Positivist science, in contrast, has prescribed the abstention from real-world events and their prediction (Schenk, 1997). Notwithstanding, prediction has been at the heart of scientific utopia since Bacon laid the foundations of empirical, positivist science. In his Nova Atlantis, Bacon writes: "And we do also declare natural divinations of diseases, plagues, swarms of hurtful creatures, scarcity, tempest, earthquakes, great inundations, comets, temperature of the year, and divers other things; and we give counsel thereupon, what the people shall do for the prevention and remedy of them" (Bacon, 1626). While prediction has until recently played little role in the earth sciences, in the last decades there has been a "rise of prediction in the earth sciences" (Oreskes, 2000) marked by scientific promises as to the predictability of earth systems and to the feasibility of integrated assessments and whole earth models (Jamieson, 2000) and the rise of prediction is marked by complementary societal demands and expectations as to predictive models for improved planning and management[12].

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[12] A recent example for the expectations of the public are the massive fires in the U.S., resonating in media articles like "Next, the fire forecast" (The Economist, 2000) and "Eine Sekunde Brandsimulation dauert eine Minute" (Hujer, 2000), suggesting that the simulation of fire dynamics is possible in principle, although it is limited by computing capacity thus far. Once such models are developped, the planning of measures (such as evacuation) would become much easier. Here, the wish is father to the thought. The public understanding of simulation and prediction is also shaped by more critical voices, e.g., by Lambel and Simiu (2000), who denounce the unfortunate, treacherous role of weather forecasts, when measures against a major oils spill in the French Atlantic were planned or by ´Die Zeit´ (2000) which points out that the only model that predicted the desastrous floddings in Mozambique was an extremely simple one, suggesting that ´big science´ is not necessarily a solution for the limitations of predictability.

In C we claim that simulation models are unsuitable for predictive purposes. When models are used in the context of science for policy (see above), the closest they can get to an anticipatory role (Costanza and Ruth, 1998) is in the Aristotelian sense of staking out the space of possibilities, i.e. the space of possible system development under a certain range of conditions and assumptions. Accordingly, models do not serve for the (faithful) representation of reality, but rather are heuristic and/or communicative tools, which refer to a space of possibles.

One is tempted to ask how planning is possible when prediction is impossible. I would argue that the underlying notion of planning is tied to mechanistic and clockwork metaphors and to the idea of an universal, privileged exo-perspective. In view of the failure of the mechanistic notion and of the predictability of future developments, the local, variable, spatio-temporal context gains importance; multiple endo-perspectives gain priority over a universal and generalised exo-perspective (Nowotny, 1996).

3.9. Nitrogen overload as an example

The terrestrial nitrogen cycle, its anthropogenic modifications through industrial agriculture and the models to represent and manage the nitrogen cycle serve as illustration in the different parts. G investigates the fate of nitrate emissions from agriculture in more detail. We conclude that while the retention capacity of landscapes and watersheds seems relatively high (around 70-80%) in the short run, in the long run, retention potentials might be depleted and memory effects play a role. Thus the nitrogen overload problem is temporarily postponed, along with its partial transfer to larger scales (e.g. the sea) and to the atmosphere (nitrous oxide production in the course of denitrification).

One typical effort to gain control over the problem is the development and application of simulation models of the nitrogen cycle (Addiscott, 1996, de Willigen, 1991, de Willigen and Neetson, 1985, Frissel and van Veen, 1981, Richter and Benbi, 1996, Vereecken et al., 1991; Engel, 1993, van Veen, 1994). Notoriously, they fail to predict important processes in a satisfactory way; e.g., an experienced farmer estimates nitrate loss with the same (un-)precision as the models (Kohl and Werner, 1988). The fundamental reasons for the lacking predictive capacity have been outlined in C and D. Notwithstanding, calls for improved simulation models persist (WBGU, 1999). Other efforts such as budget approaches differ in that they are based on potentials or capacities (see B) and are risk-oriented. Yet they also fail to address the post-normal nature of the issue, which eludes puzzle solving and disciplinary approaches, as the following points may outline: Nitrogen overload is both a local (as most sources are small scale) and global issue; the sectoral cycle of agriculture is part of a larger regional cycle; while nitrate leaching ultimately takes place on the field, the underlying reason frequently is animal production detached from the land etc. The field and the farm are but minor components of industrial agriculture, which could be considered as a "large technological system" (Hughes, 1987), involving a historically grown, entangled network of different objects (such as the farm), actors and rationalities. Industrial agriculture may no longer be a mere object, shaped intentionally by man, but a quasi-object (Latour, 1998), i.e. an object which enforces its logic and temporal reign on human subjects (Nowotny, 1995).

3.10. Science as an ecosystem?

The conventional image of science draws from a positivist tradition, as I have claimed in various sections above. Accordingly, scientific observers (for all relativity may have taught) are severed from the observed systems and, owing to their peculiar form of reasoning and methodology, posses a privileged epistemic perspective, i.e. a global exo-perspective. Thus science produces and accumulates abstract, true, objective and universal knowledge.

This type of knowledge production ("Modus 1"; (Nowotny, 1999a) takes place in peculiar institutions, which are organised according to discipline and social-cognitive hierarchy, which strive to guard their autonomy and to erect barriers of entry, in that they create a field which is "simultaneously open and public [...] as well as closed and selective. This public official space [...] is at the same time increasingly more strictly reserved to those who have met the requirements for admittance" (Bourdieu, 1991). Science holds a monopoly on certain kinds of knowledge and "it has to maintain its claims by guarding its institutional boundaries, ... its autonomy in the production of knowledge " (Nowotny, 1993, p. 64).

This image of science has come under siege. After the jolts of relativity several decades ago the discovery of complexity (Emmeche, 1997, Hedrich, 1994), associated to chaos, non-linearity, self-organisation (Krohn *et al.*, 1990), self-modification (Kampis, 1991) and endoperspectives (Atmanspacher, 1994), put into question the predictability and controllability of nature and the corresponding capabilities of science. In any case from abstract knowledge little would obtain for the concrete case (Cartwright, 1983), so that science runs the risk of running into an "objectivity trap" (Nowotny, 1993), i.e. the production of universal knowledge which is ineffectual and fruitless in concrete, real-world contexts. As to the social and societal conditions of knowledge production, science research demonstrated the contingency of scientific knowledge (Shapin, 1982) and while the demand for scientific expertise is still growing, scientific expertise is increasingly contested by the public (Nowotny, 1999b), particularly where risks are addressed (Heidenescher, 1999, Renn, 1998, Stern and Fineberg, 1996a). As Rheinberger, director at the MPI for the history of science summarises: The dream of the enlightenment of a unified image of a general science, which allows us to manipulate and control a unified and general nature seems to have finished. Instead of a privileged epistemic standpoint we have to accommodate in a world that is complex and disorderly (Rheinberger, 1996).

New modes of knowledge production, particularly in the environmental sciences and in the field of risk assessment[13], may be emerging: transdiciplinary, context-dependent knowledge

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[13] Take the Third SETAC World Congress (Brighton, U.K.; May 2000) on environmental and aquatic toxicology as an example. Sections ranged from ´hard´ topics as environmental toxicology and chemistry to risk assessment and management and "Science and policy needed to achieve sustainable ecosystems". A large part of the participants did not come from academia, but from industry, regulatory entities, NGOs etc.

production, which transcends disciplinary and institutional boundaries ("Modus 2"; Nowotny (1999a), managerial science (Nowotny, 1993) or post-normal science (Funtowicz and Ravetz, 1993a). In these images, knowledge production is recognised as indexical, i.e. as tied to certain agents operating at a certain place and time (Knorr-Cetina, 1991) and it becomes tied to specific contexts; scientific knowledge is (re-)configured for certain contexts and concrete problems and it is not tested in the abstract but under concrete and local circumstances. If science is to avoid becoming stuck in the objectivity trap, it has to develop greater context-sensitivity (Nowotny, 1993).

As future developments are not predictable let alone controllable, the local, variable, spatio-temporal context gains relevance; multiple endo-perspectives acquire priority over a universal and generalised exo-perspective (Nowotny, 1996). Sensitivity for context, local- and endo-perspectives and the testing of scientific knowledge in the concrete hint at the opening of the scientific system; e.g., the concept of post-normal science suggests an extension of the peer community, particularly to improve quality control as related to concrete problem contexts.

Knowledge organisation and integration according to such an image could benefit from the structural and transdisciplinary encoding capacities of the ´sciences of complexity´ (Nowotny, 1999a, p. 109-114), offering maximal structure with minimal accumulation. A non-linear agenda for knowledge integration would envisage science rather as an ecosystem than as a linear production line (Nowotny, 1999a, p. 112).

4. Conclusions and Outlook: A role for models in ecology

4.1. Model systems as ´models´ of ecological research?

Model systems in ecology tend to follow the ´model´ of experimental conduct and its underlying paradigms and assumptions which were established in areas like physics, chemistry or microbiology (e.g., ´closure´ B). The success of this ´model´ for the conduct of experiments is likely to be linked to the technical knowledge implicit in the experimental set-up (Hoyningen-Huene, 1989) and to the extension (encompassing the ´extendability´) of semi-laboratory conditions into the non-manipulated, real world (D). In ecology, however, the contribution of experimental model systems as well as of simulation models to the acquisition of such effective knowledge ("Bewirkungswissen"), allowing for the closure and stabilisation of the setting of natural systems may in many cases be limited. Along with object properties (such as endogenous instationarity, self-modification or ´emergence´ of system level properties), technical and social obstacles (e.g., lacking the possibility of technical realisation outside the laboratory; failure to establish an extended network transcending the boundaries of the laboratory as e.g. in biotechnology) make it difficult to establish closure and control (see B) in ecosystems. Notwithstanding, the socio-technical systems of agriculture and forestry have accumulated a remarkable amount of effective knowledge, though the contribution of science to this knowledge might be minor (Hauhs, 1999). Accordingly, it has been proposed to tap the (endo-)knowledge of the practitioners and to strive for a computer-based integration of scientific and object knowledge (Hauhs *et al.*, submitted).

4.2. Abstract states, identity and endoperspectives

The idea of an ecosystem identity, that could be determined from an exo-perspective seems to be at the heart of the essentialist notion of an abstract state and also of softer, metaphorical concepts such as integrity (Westra and Lemons, 1995) and ecosystem health (Rapport, 1995, Rapport et al., 1998). Analogies between cognitive systems and ecosystems resonate here, in particular the issues of personal identity and integrity[14]. For example, personal identity is fairly unproblematic from an endoperspective, while any identity definition from an exo-perspective is highly debatable (Nagel, 1991). Correspondingly, the fierce debates on nature conservation, on opposing images of nature as symbol, ecosystem or resource or on the ´protection´ of either processes or structures (for a review and discussion of these debates see Doppler, in press) might be circumvented by adopting an endoperspective with respect to the systems to be protected or managed. Ecosystem practitioners, interacting with corporeal systems might acquire such endoperspectives as they share the history of a concrete system in a concrete place (see the suggestion of nature conservation as utilzation technolgy (Hauhs and Lange, 1996a). Thus debates on identity, integrity and the essence of ecological systems may be rendered academic and of little practical avail.

I reckon that in several areas ecology might draw benefits from the debates in the philosophy of the mind and related fields, as they seem to be stricken by analogous problems (e.g., the on-line character of biological and cognitive systems or the generation of information and meaning). Opposing a merely naturalistic programme (Keil and Schnädelbach, 2000) and the dominance of computational metaphors (Emmeche, 1994), I would, however, consider that non-naturalist, culturalist (Janich, 1996a, Janich, 1998), hermeneutic approaches (Gadamer, 1975) and alternative metaphors (West and Travis, 1991) could also be fruitful, particularly in the context of sustainability issues.

4.3. Simulation models: Representation, knowledge organisation and conventional metaphors

Even though computer models may have heuristic and prospective value, the established understanding-prediction difference may be too restricted to obtain an adequate image of simulation models. At present, the role of computers and simulation models as instruments of knowledge organisation and communication is likely underrated. Computers and (simulation) models may be useful for the synthesis, storage and integration of scientific knowledge, for the integration of universal scientific and local object knowledge and for the teaching of ´complexity´ (Dörner, 1996). The process of modeling may be fruitful for the clarification of disciplinary knowledge and the negotiation of conflicting disciplinary paradigms and knowledge claims and for consensus building and the reconciliation of non-equivalent perspectives in science for policy (Costanza and Ruth, 1998). Emerging paradigms such as the

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[14] Note for example the resemblance between the stoical distinction of permanent attributes and states from ephemeral traits of a person (Rescher and Urquhart, 1994) and the separation of contingent ephemeral traits of ecosystems from the abstract state.

paradigm of interactivity (Hauhs and Lange, 2000a) may assign computers a new role in the organisation of knowledge and its distribution among scientists and practitioners.

The understanding of new media at their onset is often shaped by accustomed, established metaphors. Take the example of the internet which frequently is regarded as a big book (Lachmayer et al., 2000) or the computer which is regarded as a big calculator (Hauhs and Lange, 2000a). Conventional book and computer metaphors may stifle the understanding of new media and their utilisation. The emerging analytical instruments and formalisms of the sciences of complexity, simulations and computers themselves have produced an array of signs and sign systems, which still may lack reference and meaning. Utilisation, reading and interpretation frames for these signs may have to be forged and external references may have to be created, endowing them with practical and pragmatic ´meaning´. Analogical cases may be the Mandelbrot-Fractals, which were devoid of an external reference upon their creation (Gendolla, 2000) and the medium book, which in early modern times struggled to replace medieval reading habits and frames (Lachmayer *et al*., 2000). Thus it may be presumed that the (still underdetermined) pragmatic or praxeological meaning of formalisms of complexity, simulations and computers will be determined by future applications and usage.

Caution, however, seems warranted, particularly as computers and simulations contribute to the "pictorial turn" (Mitchell, 1997a, Mitchell, 1997b, Sandbothe, 1996), e.g., by visualising scientific findings and conjectures. Visualisation tends to conceal as much as it displays show (Nowotny and Weiss, 2000) and visualisation fosters affirmative, non-critical and non-reflexive tendencies (Lachmayer *et al*., 2000).

4.4. The contact of models to reality

Whether human observers ever really get into contact with the world or whether they operate only with their models has been subject to much debate between realists and constructivists. I reckon that the modelling procedure as "science in action" (Latour, 1994) is indeed largely constructivist, as it is the outcome of contingent differences, selections and choices. Moreover, I argued that models in ecology are closed systems with limited reference to a concrete, corporeal reality. Even though the model system as a theoretical construct may have no real counterpart in nature, I agree with others that theoretical entities may be real (for the opposition of entity realism an theory realism see Cartwright (1999) and Hacking (1994) and can be handled and interacted with in real-world systems.

There is a basic opposition of abstract-concrete, ideal-material, closed-open, analogous-digital or, as Gendolla (2000) puts it, the opposition of *mediality* versus *iconicity, density, individuality, irregularity* (i.e. the windows instead of the dirt on them). Scientific models usually strive for mediality in that they try to cleanse their findings from contexts and indexicality. Scientific models (i.e. both simulation models and experimental model systems) replace corporeal presence and actuality by some sort of virtuality or simulation[15], for which

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[15] The discovery of the central perspective stood at the cradle of modern science, giving rise to a supposedly priviledged ´exo-perspective´ and fostering objectification (Nowotny and Rheinberger, 2000). Yet the model procedure the central perspective invoked can be considered as a basic model of simulation (Gendolla, 2000).

reference usually has to be established ex post, extending the conditions of the simulated world into the corporeal one (D).

4.5. Scientific models for sustainability?

In sustainability issues, when the concrete interaction with concrete systems is on the agenda, *abstract* scientific models have shortcomings. Firstly, as ´simulations´ they prescribe no mode for the actual interaction with concrete, corporeal systems. While in principle they may serve as blueprints for the modification of a concrete system, they do not teach the procedures necessary to put them into practice. Secondly, scientific models do not aim at the selection of action, as they operate on the mode of observation. Thirdly, science targets pre-configurated solutions (see Knorr-Cetina (1991) on the opportunistic logic of science), instead of potentially insolvable problems, let alone problems of the ´Lebenswelt´ (Krüger, 1987). Yet sustainability issues usually are not solvable, i.e. they ask for management instead of solutions. Thus scientific knowledge may have to be reconfigurated in concrete contexts and validated for concrete, corporeal systems bringing to the fore local and endo-perspectives (Nowotny, 1996, Rheinberger, 1996).

Context-relativity and endo-perspectives, but also the notions of the precautionary principle, post-normal science and the views forwarded in recent risk research challenge the established authority of science. Science may no longer be "immune from society" and an "institutional split" might occur within the sciences, between a public policy or managerial branch and an academic branch (Nowotny, 1993). In an alternative scenario, however, major institutional or mental change may not be imminent; the science system as an adaptable evolutionary system in a functionally differentiated society (Luhmann, 1994) would gently and swiftly accommodate external disturbance (e.g., owing to changing societal demands) and internal novelty production (e.g., owing to calls for inter- and transdisciplinarity) - just as an ecosystem usually would.

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No spread of laboratory artifacts will ever prove that
the same phenomena would be observed outside the
laboratory.
Bruno Latour – The Force and Reason of Experiment

B. LIMITATIONS OF CONTROLLED EXPERIMENTAL SYSTEMS AS MODELS FOR NATURAL SYSTEMS

Daniel Haag & Gunda Matschonat

The Science of the Total Environment

In press

B. Limitations of controlled experimental systems as models for natural systems

Abstract

Experimental systems in which phenomena are studied under controlled conditions allow scientists to infer causal relationships from observable effects. Investigating ecosystems, however, scientists face complex systems. The conventional approach is to divide the system into conceptual units and to prepare experimental systems accordingly. Experimental systems are employed as models for ecosystems: scientists assume an analogy between experimental system and ecosystem, encode the experimental system into a formal system by measuring variables and decode statements from the formal system to the ecosystem.

We distinguished three types of experimental systems, i.e. laboratory, container and field setups, further divided into seven subtypes. Starting from the premises of experimental systems, we comment on the possibilities and limitations of experimentally derived causal relationships and on their significance for ecosystem understanding and prediction, illustrated by examples from soil science and the environmental sciences.

Experimental setups have a characteristic duration, degree of structural integrity, internal variability and boundaries, which relate to conceptual closure and experimental control: Control tends to be maximum on short time scales, in homogeneous setups with analytical boundaries and in systems with few parameters to be observed. Complexity is increased at the expense of control. The higher the degree of manipulation, however, the better is reproduceability but the larger is the deviation from unique ecosystems with their infinite number of factors. The material realization of closed systems is preceded by a conceptual closure of the system. Closure is relative to the domain of phenomena of interest, the theory and the list of variables selected by the scientist.

Successful decoding from experimental systems to ecosystems largely depends on the validity of the chosen analogy. Laboratory systems are idealized systems which contain a limited number of *a priori* defined variables and which are shielded from environmental influences. In contrast, ecosystems are materially and conceptually open, instationary, historical systems, in which system level properties can emerge and in which variables are produced internally. We conclude that conducting experiments, causal factors can be identified, but that causal knowledge derived from insufficiently closed systems is invalid. In ecosystems innumerous factors interact which may enhance, reduce or neutralize the effect of an experimentally determined factor. Thus experimental model systems need to be evaluated for concrete ecosystems with a concrete history. Increasingly detailed studies of isolated phenomena in the laboratory will probably not contribute much to ecosystem level understanding. Conducting experiments, scientists should aim at the maximum degree of complexity they can actually handle and they should justify the chosen analogy.

1. Introduction

Ecosystem research reflects three categories of scientific aims (Hacking, 1994; Toulmin, 1981): Firstly, the understanding and representation of ecosystems, secondly, the prediction of their behavior and thirdly, the intervention into or the management of ecosystems. Accordingly, the type of knowledge required on ecosystems ranges from explanatory over phenomenological to technological knowledge.

Investigating ecosystems, scientists face complex systems in the sense that these systems can not be described by a single theory or discipline (Kornwachs and Lucadou, 1984) leading to different non-equivalent, but legitimate descriptions of the same system (Giampietro and Pastore, 2000). Moreover, ecosystems are open with regard to matter, energy and information, they are instationary on all scales, i.e. temporally variable (Lange, 1998; Lange, 1999) and spatially heterogeneous. Ecosystems thus are difficult to treat experimentally and theoretically, although they may be relatively easy to handle practically, as in the case of agricultural or forestry systems (Hauhs and Lange, 1996).

Experiments serve to reconstruct partial aspects of the ecosystem and to infer if-then statements or causal relationships, in which the if-part describes what has been prepared by the scientist and the then-part the ensuing course of events (Janich, 1992, p. 234). The experimental setups, which are prepared to exclude undesirable factors, differ from experiment to experiment with respect to their material realization and particularly to the degree of idealization.

Different types of experimental systems serve as models of ecosystem aspects, i.e. of certain processes or structures. The term model refers to a material or ideal (re-)production of an object by means of analogies realized by a cognitive subject (i.e. an observer) (Ehmke, 1997). Analogies are similarities among different objects concerning certain aspects or properties. They permit the inference of probable properties of object B from the properties of object A (Löther, 1997). Scientists assume that material (structural) or conceptual (functional) analogies exist and can be used to infer ecosystem features from experiments. This is the basis for our understanding of experimental systems as models.

When scientific observers reconstruct ecosystem aspects conceptually and materially in experimental model systems they firstly chose the domain of phenomena to be represented. Secondly, they need to select variables which are necessary to represent that domain from the infinite list of variables of the material system (Ashby, 1976, p. 40). The system which they obtain is thus a list of variables which abstracts from the material object. Thirdly, they build an experimental model, consisting of a conceptual system part and a material realization in an experimental setup.

Selecting variables, the scientific observer establishes a reading frame for the system. For example, ecosystems may be ´read´ from a biogeochemical or a population ecology perspective, resulting in different descriptions of the same system. Reading frames are embedded into a network of theories (Hanson, 1958) and preunderstanding (Gadamer, 1975) and in this sense are theory-laden. The reading frames of the experimental setups are based on certain premises concerning time, space, and closedness (control).

In this paper we will conceive experimental systems as models of ecosystems and will discuss the nature of this modeling relation from a biogeochemical perspective. Taking three typical experimental setups in the environmental sciences, i.e. laboratory experiments, container/pot experiments and field-scale experiments, further divided into seven subtypes, we will show the conceptual and technical steps leading to the idealization and to the closure of these model systems and we will discus their underlying premises as to time, space, and closure. Confronting them with a notion of ecosystems that encompasses the concepts of emergence and self-modification, the limitations of the models concerning transferability to the ecosystem scale will be highlighted. Finally we will comment on the use of experiments in the environmental sciences.

2. Modeling relations

Figure B.1 illustrates the relation between a material system which is governed by its causal structure and the formal system into which scientists (as observers) encode the material system by measuring certain variables (Rosen, 1991). Variables are quantifiable entities, which represent factors capable of causing concrete effects. Each measurement of a determined variable highlights certain features of a system and assigns them quantitative values, relegating all other features, both known and unknown, to the system background. In the formal system, scientists infer sets of functions from the observed if-then relationships.

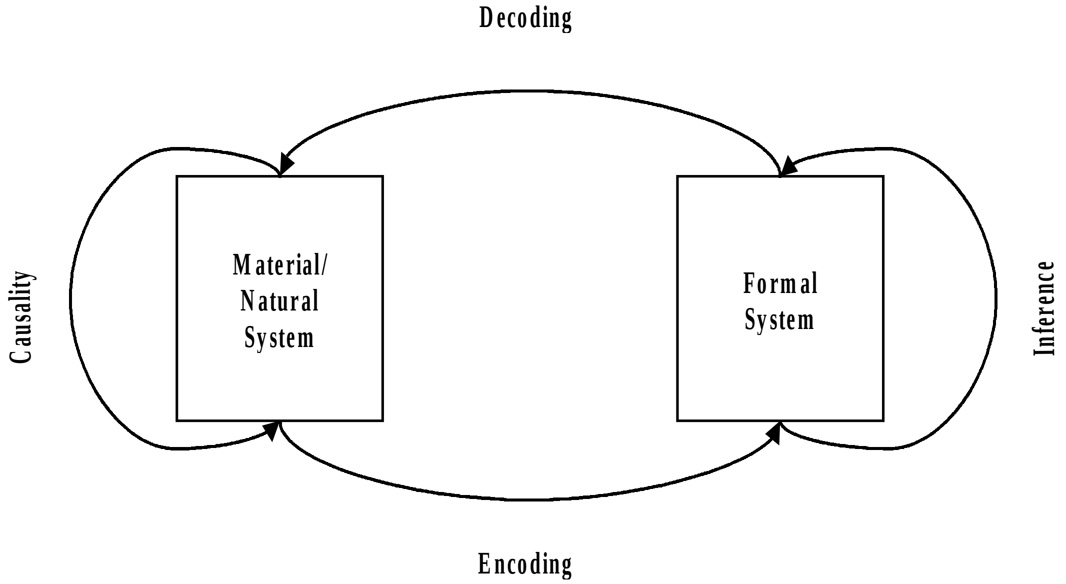

Figure B.1. Modeling relation between a material system and the corresponding formal system. The material system is encoded by assigning quantitative values to certain variables. The sequence of encoding - inference - decoding aims at the representation of causality in the material system (adapted from Rosen, 1991).

Commonly, the inference structure of the formal system is taken to represent the causal structure of the material system. In the decoding step, statements on system behavior derived from the formal system are transferred to the material system. This procedure entails a number of conceptual problems, discussed in detail by Rosen (1991). A modeling relation is established between the formal system and the material system. Similarly, modeling relations between different material systems can be invoked, e.g. when a mesocosm experiment is taken to represent an ecosystem (Boudou and Ribeyre, 1997), which are acompanied by peculiar problems: e.g. the problem of spatial representativity in sampling in that a sample taken at one specific location is supposed to stand for a larger spatial unit or for other locations. For practical reasons, adult trees are sometimes substituted by juvenile trees in experiments (Dieffenbach et al., 1997, George et al., 1999). In addition to the issue of spatial representativity, the use of juvenile trees as material models for adult trees brings about the problem of their different developmental stages.

Statements derived for the spatially explicit experimental system are frequently extrapolated to larger spatial units if the experimental system is regarded as characteristic for, e.g. a certain landscape section. The experimental system serves as a material model for the larger explicit geographical unit (material-material analogy) (Matzner and Tenhunen, 2000). In an extreme case of analogical inference, the model system (e.g. a specific podsol soil) is encoded into a formal system which is taken to represent an abstract or idealized system type (e.g. podsols in general; formal-formal analogy). When we infer statements on ecosystem behavior, we thus usually apply a three step procedure (fig. B.2).

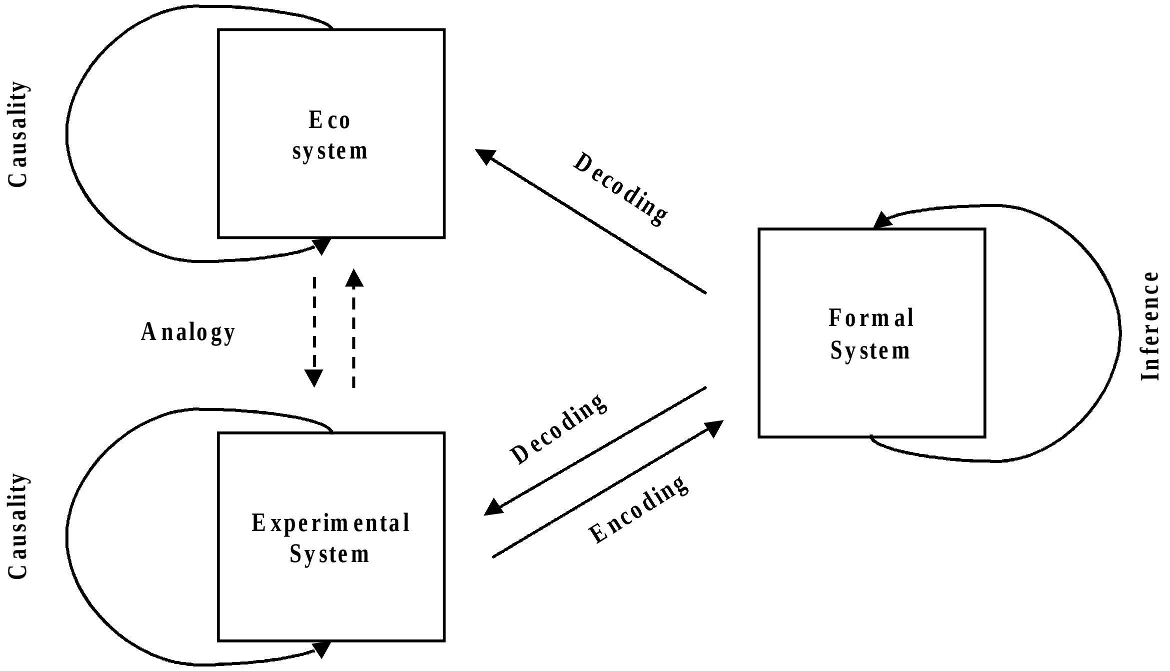

Figure B.2. Experimental systems as models of ecosystems. A modeling relation (analogy) between ecosystem and experimental system is invoked. The experimental system is encoded into a formal system, which is supposed to be valid for the ecosystem as well. Decoding is the transfer of statements from the formal system to the ecosystem.

The three steps encompass (a) an analogy between two material systems, i.e. an ecosystem and an experimental system, (b) a material-formal encoding step, in which the experimental system is encoded and (c) a decoding step, linking the formal to the ecosystem. The observer thereby assumes that the two material systems, i.e. the experimental system and the ecosystem realize a common formal system (Rosen, 1991, p. 62). When decoding we apply the formal relationship, e.g. process and system descriptions obtained under laboratory conditions, to the ecosystem.

Scientists choose from a multitude of experimental setups establishing material-material modeling relations (analogies) which entail different assumptions and difficulties some of which we will highlight in the following. The underlying questions will be to what extent the analogies invoked by the different setups are justified and whether the encoding of the setup is valid.

3. Experimental Setups

The material realization of experimental setups is a laborious task that requires a high level of craftmanship (Hacking, 1992). Focussing on terrestrial ecosystems and the soil compartment (but exemplary for the environmental sciences in general), we distinguish three main types of experimental setups, i.e. laboratory, container and field experiments, which we further differentiate into seven subtypes:

1) laboratory setups in which purified, fabricated and synthesized components like strains of microorganisms, clay minerals from geological deposits or synthetic oxides (Kretzschmar et al., 1997b; Kretzschmar et al., 1997a), purified or synthezised organic (Alewell, 1993; Kretzschmar et al., 1997b), and artificial solutions play the part of the respective natural components, but with idealized features (**Lab - idealized components**);

2) laboratory setups with ´natural´ components like microorganisms on their natural substrate (Küsel and Drake, 1996), soil from the site in question (Zander et al., 1999) and natural waters, but divested of their natural structural arrangement (**Lab - natural components**);

3) container setups with structurally homogenized soil like in greenhouse containers (George et al., 1999) or rhizotron experiments (Dieffenbach et al., 1997) in which plants grow in homogenized soil (**Container - homogeneous**);

4) container setups which use structurally intact soil, like in undisturbed soil cores and columns used to study solute transport or chemical composition (Hantschel et al., 1988; (Vogt and Matschonat, 1997) and soil physical characteristics (**Container - undisturbed**);

5) field experiments like tracer experiments to study solute movement (Zander et al., 1999), acidity-exclusion experiments (Matschonat and Falkengren-Grerup, 2000), liming of parts of a forest stand (Kaupenjohann, 1989), or fertilizer experiments with replicates on plots (**Field - plot scale**);

6) whole-ecosystem manipulations with respect to acidity (Moldan et al., 1998; Wright et al., 1988), nitrogen, or drought (Wright and Rasmussen, 1998) (**Field - whole ecosystem**);

7) field observation without direct manipulation (reducing the risk of unintentional side effects), like in monitoring under conditions of "naturally" changing (Dillon and LaZerte, 1992) or differing boundary conditions (Matzner and Tenhunen, 2000; Schulze and Ulrich, 1991), space-for-time substitution (Bäumler et al., 1997; Crews et al., 1995), or use of spatial variability to evaluate laboratory-derived relationships (Ross and Barlett, 1995) (**Field - not manipulated**). In space-for-time substitution spatially explicit systems are supposed to be linked by a common developmental sequence, so that from sampling ecosystems at distinct developmental stages and at different locations, the future development of the systems in the sequence can be inferred (Zimmermann et al., 2000). This setup combines the issue of spatial representativity and the problem of the idealization of the course of development.

4. Experimental closure and control

"A well-designed experiment is constructed to allow us to infer the character of the cause from the character of its more readily observable effects" (Cartwright, 1983, p. 83). Preconditions for the inference of causal relationships are the manipulation of the cause to "look to see if the effects change in the appropriate manner" (Cartwright, 1999) and the closure of the experimental setup. Closed systems, however, are not just found, but have to be created and maintained (Radder, 1986).

We distinguish *conceptual closure* which aims at conceptual closedness and which is a theoretical concept from *control* or experimental closure which refers to the act of establishing and maintaining closedness in explicit, material settings. Both experimental control and conceptual closure are required to obtain closed experimental systems and valid causal relationships.

To control the influence of external factors and fluxes from the outside to the inside and vice versa, boundaries need to be established and maintained. The issue of boundaries will be discussed below.

The way how closure is established and maintained and the degree of concomitant control over internal variables and external factors varies widely among the setups described above. They usually have a characteristic duration, degree of structural integrity and internal variability. Figures B.3 a-d demonstrate the relationship of these characteristics with the establishment and maintenance of control.

4.1. Temporal scales

Laboratory setups, in general, are carried out on short temporal scales and consequently need only be kept closed during a relatively short time (Radder, 1986), while container and field experiments usually operate on longer time scales (fig. B.3a). To establish control at the beginning of an experiment, the initial conditions concerning the relevant variables need to be known. The accessability of these variables is high in laboratory setups, as these systems are constructed by the experimenter according to his notion of closure. The verum factum principle of modern science which attributes truth and understanding only to systems constructed by man (Hösle, 1990) reflects this assumption.

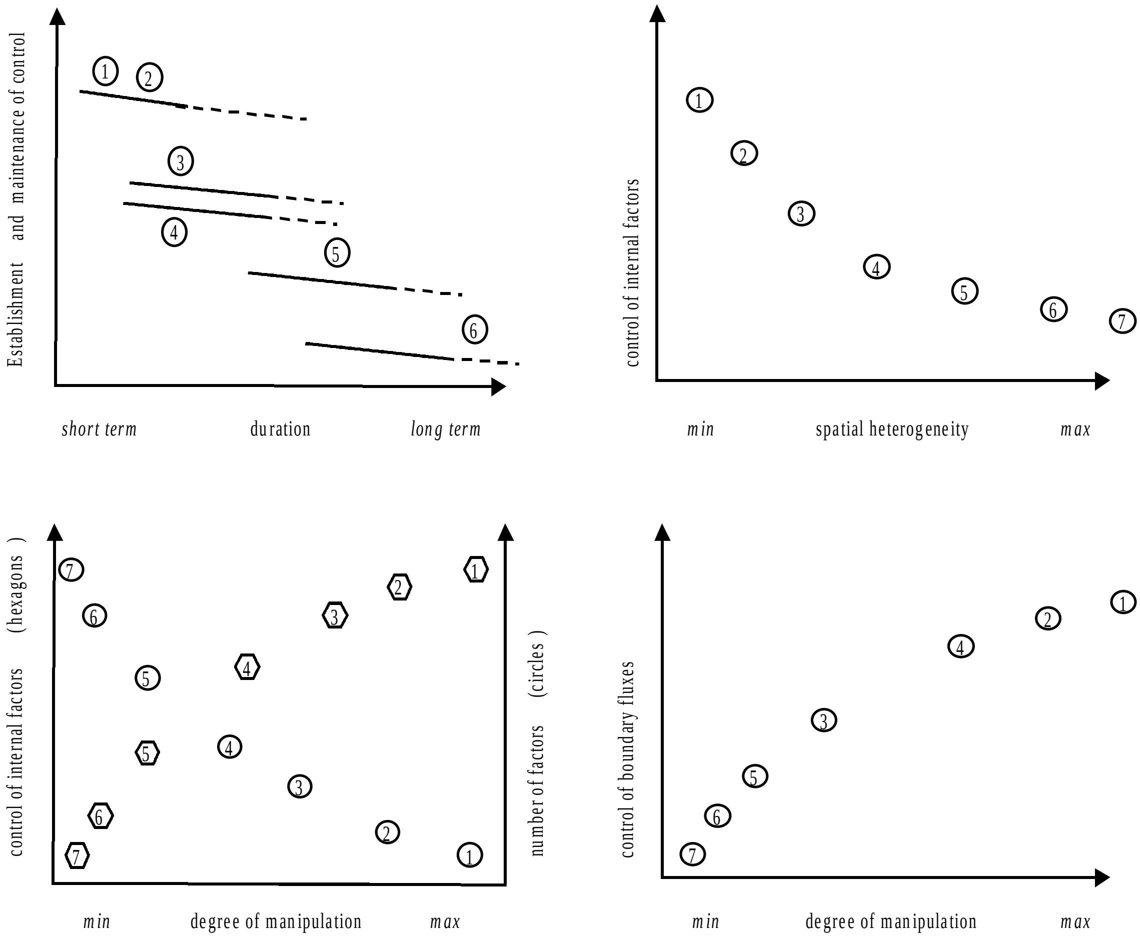

Figure B.3. Characteristic features of experimental setups with respect to time, space and control. Numbers refer to the experimental setups: 1 lab - idealized components, 2 lab - natural components, 3 container - homogeneous, 4 container - undisturbed, 5 field - plot scale, 6 field - whole ecosystem, 7 field - not-manipulated.

Figure B.3a. Characteristic duration of experiments and control. The typical duration of experiments is indicated by straight lines, prolonged in a few cases (dotted line). Control tends to decrease in the course of each single experiment (indicated by the slope).

Figure B.3b. Relation between spatial heterogeneity and control of internal factors. The more homogeneous the setup, the better can internal factors be controlled.

Figure B.3c. Relation between degree of manipulation and control of internal factors (hexagons) and number of factors and complexity of interactions (circles). Complexity increases at the expense of control.

Figure B.3d. Relation between degree of manipulation and control of boundary fluxes. The more manipulated a setup, the better can fluxes across boundaries be controlled by the experimenter.

As compared to laboratory experiments, potentially more factors come into play in container and field experiments, and their interrelation as well as spatial and temporal variability is often only incompletely known. Along with the increasing number of factors more effort has to be spent to exert control.

In the course of an experiment, control tends to decrease as the system may evolve, and new variables and interactions among causal factors may appear. Maintenance of control on the pragmatic side requires a high degree of craftmanship to exclude disturbances and to impede unwanted system evolution: "Much of scientific practice can be understood as the open-ended, creative and embodied work involved in the practical management of resistances; closure can be seen [...] as a successful outcome of this management process" (Pickering, 1990, p. 216). For example, in experiments with soil cores, algal growth may take place on container walls and tubes, and formerly sterile setups may become recolonized by micro-organisms. Such system evolution also poses conceptual problems discussed below.

4.2. Spatial structure and heterogeneity

The environmental sciences have focused on the issue of heterogeneity (Böttcher, 1997; Manderscheid and Matzner, 1995), because of the conceptual, epistemic and practical problems it poses. In terrestrial ecosystems, virtually all parameters are linked to structure and are spatially distributed; examples are hydraulic conductivities or temperature. Heterogeneity makes sampling the most common practical problem: When the investigation aims at statements for a spatially explicit system a limited number of samples must suffice to represent the whole system. The appropriate number of samples can not be known in advance, however, and only estimated afterwards. Depending on the parameter and the spatial heterogeneity and temporal variability in the measurement period the number of samples necessary to fulfil certain precision demands would often exceed the number of samples actually taken as was estimated for soil solution sampling with suction cups (Manderscheid and Matzner, 1995) or ammonium sorption isotherms (Smethurst et al., 1999).

The spatial structure of ecosystems is the result of an interaction of processes on different temporal and spatial scales (O´Neill et al., 1989; Risser and Box, 1987; Wiens, 1989), but it is often assumed to be temporally invariable and thus regarded as an internal boundary condition. The spatial heterogeneity of ecosystems on all scales limits practical and epistemic access to structure: Studying spatial structure interferes with the system (Oreskes, in press). The spatial distribution of parameters can only loosely be restricted by measurements (Lange, 1998) and structure is unknowable at any scales of real interest (Beven, 1996).

To handle heterogeneity conceptually, scientists resort to continuum theory, "in which a material with heterogeneous parts is treated as if it were a single homogeneous entity: the continuum" (Oreskes, in press). Thereby, new properties are obtained, like the permeability of porous media, which permit scientists to describe heterogeneous material in a tractable manner. This way, however, fine-scale information on structure is lost.

The degree of spatial heterogeneity and the degree of control of structural parameters and internal factors linked to them is inversely related (fig. B.3b). In laboratory experiments, structure can be constructed, allowing for structural parameters which can be easily accessed epistemically and controlled (reflecting the verum factum principle). Yet, the homogenous setting of laboratory experiments can not be decoded easily to natural systems as in them, heterogeneity plays a prominent role.

Internal variables can be controlled more efficiently the higher the degree of manipulation of the setup is (fig. B.3c). Yet the number of variables and the complexity of a setup usually are reduced with increasing degree of manipulation. A high degree of manipulation and the concomitant reduction of complexity often increase control and reproduceability. The number of factors that can thus be handled in controlled experimental systems is notoriously low, e.g. in a poster session on terrestrial ecology only one out of 36 experimental systems investigated an ensemble of more than three factors (including time as a factor) (Caswell, 1988).

As the degree of manipulation increases and the number of factors studied decreases, the analogy between the manipulated, reproducible experimental system and the complex, unique ecosystem (Breckling, 1992) becomes forced.

4.3. Boundaries

Control of boundary fluxes is related to the degree of manipulation (fig. B.3d). The more manipulated a setup, the better can fluxes across boundaries be controlled by the experimenter.

Boundaries control fluxes between the system and its environment. According to hierarchy theory, boundaries form where there is a significant gradient in concentrations of energy, matter or information. At boundaries, changes in interaction rate and strength occur (Ahl and Allen, 1996, p. 165) and internal flows and cycles are more rapid and intensive than interactions with the environment. Process rates are high within the system (termed holon) and decline towards its boundaries (Ahl and Allen, 1996; Müller, 1992). Within this concept, boundaries are organized by and thus belong to the system and have to be defined empirically (self-organization; (Paslack, 1991) contrasting with the conventional, analytical notion of boundaries which are imposed externally and *a priori*, instead of being based on empirical criteria.

In whole ecosystem manipulation, scientists try to make use of boundaries that are based on gradients of energy, matter (Müller, 1998) or information (Hauhs and Lange, 1996). In watershed experiments, for example, gradients of potential energy delimit the system under study so that boundaries need not be imposed artificially (externally) upon the system, while they still can be controlled considerably. This type of boundaries comes closest to the notion of boundaries forwarded by hierarchy theory and thus to the idea of a `natural´ boundary, shaped by the system and not imposed externally.

In many field experiments, this conceptual notion of boundaries, however, does not solve the issue of the spatial location and identification of boundaries. For practical reasons, boundaries may still have to be defined analytically to get the studied system closed. Moreover, as in ecological systems no parameter can be regarded as spatio-temporally constant, system definition requires the choice of in- and output boundaries not only in space but also in time (Hauhs, 1992). The precise location of even the analytically defined boundaries is often unknown and the assessment of boundary conditions remains vague in the practice of field investigations (Hoffmann, 1997) as heterogeneity and variability at the analytical boundaries decrease control over the fluxes of matter, energy and information.

In laboratory experiments boundaries can only be conceived analytically, are external to the system and are (and can be) arbitrarily imposed upon the system by the scientist. Boundary establishment is thus conceptually trivial and merely an issue of material realization. When a laboratory experiment is set up dexterously, control of boundaries and boundary fluxes is very high.

Decoding would pose no major problems in field studies in which boundaries and scales correspond to the boundaries and scales of the system for which statements are to be derived. However, there is no criterion telling scientists a priori whether the scales of an experimental system match the scales of an ecosystem. In the case of laboratory experiments even more severe conceptual problems arise in the decoding step, as laboratory experiments are arbitrarily bounded in space and time, without regard for the scales on which relevant processes operate in the ecosystem.

4.4. Hierarchical levels and upscaling

The reductionist assumption of "microdetermination" (Klee, 1984), i.e. the assumption that the state of the whole (ecosystem) is determined by its components, allows for the extrapolation of their properties to the higher scale. Consider studies on denitrification as an example for how the different setups address issues on different scales or hierarchical levels. In laboratory setups, oxygen, nitrate and carbon control denitrification (Ferguson, 1994). These are primary or proximal factors steering processes at the microphysical or cellular level (lab - artificial or natural components). Distal factors operate on higher scales, constraining the proximal factors on the lower level (Groffman et al., 1987). In undisturbed soil cores for example, natural structure determines the spatial distribution of carbon, oxygen and nitrate so that microsites with different characteristics come into being. Structure thus delimits the range of potential fluxes or rates of denitrification that can possibly occur. As the spatial and temporal scales of investigation increase further, one has to focus on distal rather than proximal factors (Groffman et al., 1987) and, following the reductionist upscaling rationale, one needs to account for more causal factors and more complex interactions among them. In field setups, microtopography, rainfall (Ball et al., 1997) and seasonal patterns of C availability (Groffman et al., 1987) among others are distal factors (field - plot scale). In whole ecosystem experiments, e.g. in catchments, hydrologic and pedologic processes vary with topography and regulate the factors controlling denitrification at the microscale level (Corre et al., 1996). Experimental control of this network of factors, factors that may not be easily accessible (e.g. due to their spatial and temporal distribution), may become increasingly difficult.When upscaling from abstract process descriptions obtained in the laboratory, where there are only a limited number of factors interacting under idealized conditions, to the ecosystem scale, one is faced with unique aspects of the concrete system, such as microsites (Groffman and Gold, 1998) and land use history (Addy et al., 1999). Accordingly, whole ecosystem experiments have revealed a number of unexpected insights one would not have arrived at on the basis of laboratory experiments, or even field experiments, alone (Emmett et al., 1998; Schindler, 1998; Wright and Rasmussen, 1998).

5. Conceptual closure

The material realization of experimentally closed systems in the laboratory is preceded by a conceptual closure of the system under study. Closure roughly implies that the inside of a system is not influenced by the outside. However, this does not imply the closure to *any* conceivable influence, but has to be relativized in two ways (Radder, 1986), introducing relevance criteria into the description: Firstly, only such influences are considered which are relevant to the domain of interest. Secondly, closure is only relative to the theory taken to be valid for the description of a system. The theory specifies the number of types of possible influences upon the system by the environment. When scientists close systems conceptually, they thus have to choose the domain of phenomena of interest, a theory and a corresponding list of variables. The theory encompasses the state of the art and the preunderstanding of a system and it guides observation; at this stage experiment and observation become ´theory-laden´ and excluded factors become noise/background. For the system under study a set of hypothesis is derived from the theory, forming a conceptual model of the system which hints at the factors of relevance. The criteria on which model and list of variables are based are both explicit and implicit and are derived from different sources. In different areas of science, different perspectives on natural systems prevail, giving rise to the construction of different, non-equivalent descriptions of the same system. For example, soil population biologists would describe a section of the soil in different terms as compared to geochemists (O´Neill et al., 1986) and hence would compile a different list of variables. The formation of scientists and the tradition of their area of science provides them with both explicit and implicit criteria for the choice of relevant variables. When certain variables are chosen to be ignored, practical reasons may play a role as well, as some variables are too difficult or expensive to measure. However, to achieve a valid system description and closure, all relevant factors have to be taken into account. The unwarranted exclusion of factors may invalidate closure and thus observation easily (Cartwright, 1983). As conceptual closure predetermines both the results and their interpretation it is a crucial step in all experimental work.

6. Decoding from model systems to ecosystems

If the aim of experiments in laboratory and field is to derive statements about ecosystems and their behavior, we have to ask how the experimental and conceptual closure of experimental systems relate to the openness of ecosystems and what consequences concerning prediction, understanding and intervention arise from the discrepancy between closed experimental systems and open ecosystems. Ecosystems differ from experimental systems in that ecosystems are (a) thermodynamically open and subject to a broad range of external influences, in that they are (b) conceptually open, due to emergence of properties and production of new variables (self-modification) and in that (c) time is organized internally.

6.1. Thermodynamical openness

The behavior of ecosystems usually is, for predictive and management purposes, conceived as the relationship between external input and resultant output. Although both boundaries and matter and energy fluxes across boundaries are difficult to assess, external input is taken as an external driving factor or boundary condition.

No data set, however, can completely represent the range of naturally occurring conditions so that ecosystem behavior can only be assessed for the range covered by the respective data set (Konikow and Bredehoeft, 1992), which limits inference of ecosystem behavior. Moreover, boundary conditions may change with time, e.g. due to atmospheric deposition or climate change, and supposedly external boundary conditions are not independent from the ecosystem because of the increasing importance of feedback at larger scales (Jarvis, 1995; Jarvis and McNaughton, 1986) as the example of the Amazonian rainforest and its self-organized climate demonstrate (Salati and Vose, 1984).

6.2. Conceptual openness

In laboratory and field experiments isolated ecosystem components and their properties are studied. The reductionist assumption of microdetermination (Klee, 1984) implies that at the system level there are no degrees of freedom (Hoyningen-Huene, 1994), because the state of the whole is exclusively determined by its components. However, on the (eco-)system level properties and constraints may emerge which are unknowable or only empirically assessible a posteriori (Hoyningen-Huene, 1994). Emergent properties may arise relative to a certain description (descriptive emergence), e.g. permeability of porous media is a property that does not exist on a microscopic level but emerges from the interrelation of the component particles on a macroscopic level (Oreskes, in press). In hierarchically organized systems, in which higher levels exert some control over the behavior on lower levels, also constraints may emerge. Hierarchical constraints frequently are related to self-organization and are invoked in ecosystem theory (Joergensen et al., 1992; Müller, 1996; Müller, 1997) and the earth sciences (Werner, 1999) to explain whole-system behavior. Due to emergence, properties derived from laboratory or field experiments may be subject to unpredictable changes or constraints on the ecosystem level. Factors from lower hierarchical levels (such as determined in laboratory

experiments) might even be irrelevant on the ecosystem level and the identification and measurement of ecosystem level variables might be more useful.
In the conceptual closure of laboratory and field setups the type and number of variables are specified a priori and remain fixed throughout the experiment. Ecosystems, in contrast, are self-modifying systems (Kampis, 1991), which produce and destroy their own components during their typical activities. These systems constantly produce internal novelty, new variables and de novo interaction of components (Kampis, 1994), which can only be defined a posteriori. Ecosystem thus are conceptually open.

6.3. System time and history

Problems of structure and heterogeneity in space have been studied intensively in ecosystem research but the structure of time has received little attention. Laboratory and field experiments refer to a Newtonian notion of universal time (Mittelstaedt, 1980), which is external to the studied phenomena and is consequently regarded as a parameter (parameter time). Accordingly, the abstract state of a system, in which essential features are supposedly captured, can be updated by a temporal transition function in which time is a parameter. Even in this conceptual framework, non-linearity and sensitivity to initial conditions may lead to considerable deviation of computed and actual behavior (Cambel, 1993; Ott, 1993; Zimmer, 1999). Yet ecosystems are self-organized, hierarchical systems in which subsystems experience and organize time internally on different scales (system time (Kampis, 1991; Kampis, 1994; Kümmerer, 1996). External parameter time fails to capture the features of internal system time, in which time is tied to the phenomenon. Moreover, parameter time assumes that history is irrelevant for the calculation of future states because it would already be captured by the initial conditions. The history of ecosystems however, cannot be reduced to an abstract state and a set of initial values (Lange, 1998), (Ebeling et al., 1990; Hauhs and Lange, 1996). Ecosystems display memory effects and non-trivial long-range correlations (Ebeling et al., 1995, pp. 48-50) which demonstrate that they are historical systems.

All in all, experimental systems resemble trivial machines for which there is an operator relating input to output. Experimental systems can be defined a priori and are predictable and independent of their history (Foerster, 1998). Ecosystems, in contrast, should rather be viewed as non-trivial machines, which are definable only a posteriori and in which the historical record of operations influences present operations.

7. Causal factors and their relevance

In view of the limitations of experimental systems as models for ecosystems, the question is what we can learn from these models. Following Nancy Cartwright, we do not question that causal factors which have the characteristics of potentials or capacities to bring about certain effects act in nature and that it is possible to identify experimentally these causal factors (Cartwright, 1983; Cartwright, 1994). To gain pragmatic relevance, these causal factors need also to be accessible in practice because the factors identified in the experiment augment our strategic knowledge only if there is a chance to actually employ or interfere with them under field conditions. Prediction of the actual behavior from the knowledge about the capacities is not possible, however, as other factors may enhance, reduce, neutralize or even overcompensate the effect of that particular factor in the concrete natural system. This fact has been pointed out by laboratory scientists also ("It is essential to keep in mind that thermodynamics tell us what is possible or impossible in energy terms and says nothing about which reactions will occur [...]" (Bartlett, 1999), p. 375).

Consider charge development of organic matter in acid forest soils as an example. The theoretical conception is that exchangeable cations are unspecifically bound to single organic functional groups that carry variable negative charge depending on the variable pH, and the sum of which constitutes the cation exchange capacity (CEC). Results from laboratory experiments with soil (lab - natural components), such as shown in Figure B.4a (data from Matschonat and Vogt, 1997), suggest that pH-dependent protonation and deprotonation of the functional groups has a large capacity to modify the CEC. Studies with muck, which was used as a model substance to represent soil organic matter and whose concentration of organically complexed aluminum was manipulated in the laboratory (lab - idealized components), indicate also for the variable ´organic aluminum´ a large capacity to affect organic matter CEC (Fig B.4b, data from Hargrove and Thomas, 1982). However, Figure B.4c shows that for unmanipuled samples taken from a range of soils in the northeaestern U.S. (field - not manipulated), already the variability of the factor ´organic carbon concentration´ alone accounted for about 90% in CEC variation (Ross and Barlett, 1995). This leaves not much residual variability to be explained by other potential factors influencing CEC, such as protonation/deprotonation of organic functional groups and complexation of aluminium by organic matter, however large their capacity seemed to be in laboratory studies.

So why is it that experimental accounts sometimes turn out to be valid outside the manipulated experimental conditions, under field conditions? Natural systems can in some cases be arranged to mimick the setting of the model system; to extend the laboratory conditions, the question is "how to transform the farm into a laboratory?" (Latour, 1994, p. 249). Following such a rationale, e.g. in agriculture or forestry, a high degree of control of the variables of interest can be achieved (which includes the possibility to handle the system as if it was a trivial machine as to certain features). Yet the experimental account fails to work in ecosystems in which such purposeful interference is not possible or not desired.

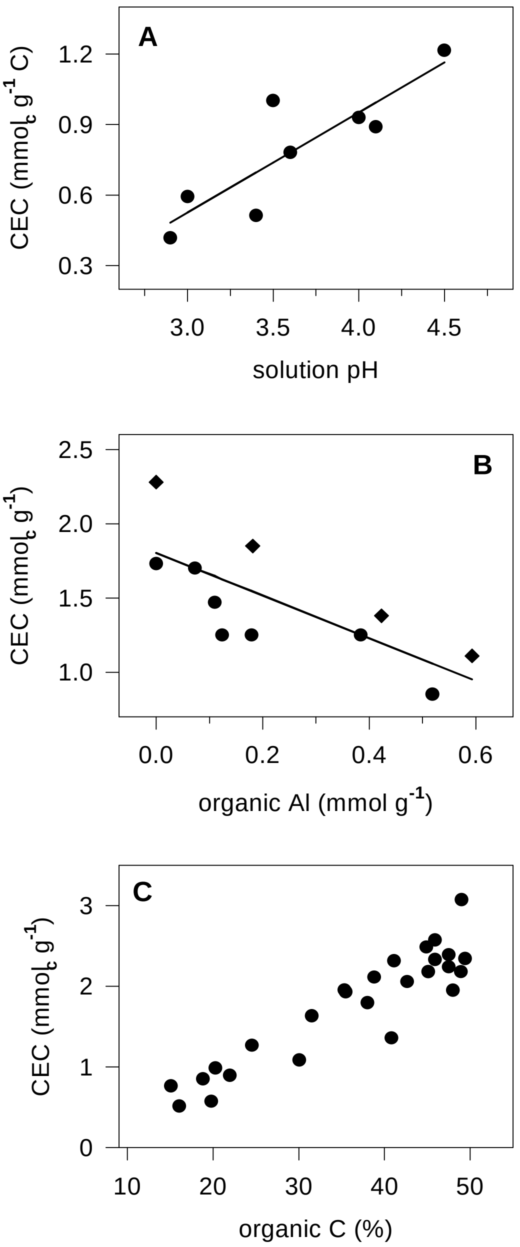

Figure B.4. Some factors affecting the cation exchange capacity (CEC) of organic matter. A: Laboratory relationship of the CEC of organic matter-rich forest soil samples with experimentally manipulated solution pH (data from Matschonat and Vogt, 1997); B: Laboratory relationship of the CEC of muck samples with experimentally manipulated concentration of organically complexed Al (data from Hargrove and Thomas, 1982); C: A field study on unmanipulated forest soil samples, making use of the spatial variablility of the variables (data from Ross and Barlett, 1995). Variability on organic carbon concentration alone already accounted for most of the variability in CEC. The pH range was 2.7-4.2 and organically complexed Al was 0.1-2.6 mmol$_c$ g^{-1} carbon in this study.

8. Conclusions

We have regarded experimental setups as models for natural systems insofar as in an encoding step, a closed system is built from which in a decoding step, statements on ecosystems are derived. These models are dualistic in that they consist of a theoretical part (formal system) and a material part (material system), both of which have to be closed to allow for the inference of causal relationships and the identification of causal factors. A key issue in the identification of causal factors is whether the list of variables is complete with respect to the studied phenomena (Cartwright, 1983). Causal knowledge derived from insufficiently closed systems is invalid, even for the experimental system itself. As it is not possible to know in advance whether all relevant factors have been accounted for, any conceptual closure has to be checked empirically.

As experimentally derived causal factors designate no more than capacities, both possibilities and limitations arise when they are transfered to ecosystems. While good experimental practice has to provide for closed systems with stable settings to allow for causal inference, in ecosystems the setting is not stable. The better the experimental system is prepared and manipulated to control internal variables and external factors and to maintain stability, the more it deviates from natural conditions, in which heterogeneity, variability and instability prevail and in which many factors interact in ways that have been shaped by the individual history of the system. Thus even if the list of variables is complete for an experimental system, in the ecosystem additional factors come into play which interfere with the factors of the experimental account. Therefore, the prediction of ecosystem behavior from experimentally derived factors is seldom possible.

While knowledge transferred from model systems does not allow for prediction, causal factors and their capacities can help to identify factors that enhance or impede the propensity for certain events to take place, e.g. in risk assessment. Risk factors and enhancing/attenuating factors may then be observed or interfered with. Due to the uncertainty conveyed by the capacity character of causal factors, the precautionary principle should hold for scientific knowledge claims concerning ecosystems.

What follows from the concept of capacities for the conductance of experiments? The experimental setup should aim at the maximum degree of complexity that the experimenter can actually handle. This degree of complexity is determined by the scientist´s knowledge and by his or her technical means but in practice, is also limited by resources such as time. In any case, when starting from simple experimental systems an integration of more complexity should be aimed at, approaching ecosystem conditions stepwise. Long-term behavior may only be revealed by long-term experiments, but these are costly and the strategic knowledge derived from them may come too late. Substituting space for time is one way of obtaining hints at long-term ecosystem behavior, although such results are to be interpreted cautiously as they construct a space/time analogy from concrete, singular environmental settings. When scientists claim their experimental system to be models of ecosystems, they should justify the chosen analogy. The more the experimental setup deviates from natural conditions (e.g. by arbitrarily reduced the number of factors), the more it calls for justification.

Experimental model systems require evaluation as to their explanatory and predictive capacity for natural settings. To decide how a generalized model system relates to a concrete setting, i.e. a concrete system with a concrete history in a concrete location, it needs to be tested with and adapted to the specific system itself. The comparison of one model system (or the statements derived from it) with other models systems or with mathematical simulation models says nothing about their validity under non-manipulated, open system conditions. One must even be ready to revise the linkages of factors in conceptual models when these are applied to concrete systems. It is obvious that one hundred percent explainability can not be obtained and maybe, increasingly detailed studies of isolated phenomena in the laboratory will not contribute much to our ecosystem level understanding.

Even though this capacity-based approach to ecosystems seems workable, we did not intend to exclude alternative approaches or imply that the capacity-based approach is the most adequate or efficient one. Other promising approaches might, among others, be based on complexity measures, local knowledge (Hauhs and Lange, 1996; Lange et al., 1997) and phenomenological laws.

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Naturgemäßes Chaos statt unrechtmäßiger Ordnung!

Graffito

Um die eigentliche Artischocke zu finden, hatten wir sie ihrer Blätter entkleidet.

Ludwig Wittgenstein - Philosophische Untersuchungen

C. BIOGEOCHEMICAL MODELS IN THE ENVIRONMENTAL SCIENCES: THE DYNAMICAL SYSTEM PARADIGM AND THE ROLE OF SIMULATION MODELING

Daniel Haag & Martin Kaupenjohann

Hyle - International Journal for the Philosophy of Chemistry
2000, Vol. 6, 117-142.

C. Biogeochemical Models in the Environmental Sciences: The Dynamical System Paradigm and the Role of Simulation Modeling

Abstract

Dynamical systems are *the* paradigm for the representation of complex systems. The fixed encoding in a closed set of equations, however, contrasts with the openness of biogeochemical systems. Parameter identification is a major problem in biogeochemical systems and calibration of parameters converts models into ´fitting machines´. Openness, self-modification and historicity of biogeochemical systems make non-trivial predictions of future outcomes impossible. Notwithstanding, simulation models serve as instruments of synthesis and have heuristic value to challenge existing data and theories. The modeling process itself, as a learning and communication process, can be a mode of coping with different types of complexity.

1. Introduction

System metaphors pervade ecology and the environmental sciences. System metaphors are characterized by a set of basic attributes, i.e. interacting parts, organization, collective behavior and whole system functionality (Paton, 1993). Machine and circuit are concepts associated with system metaphors. The circuit concept of eco-systems accounts for fluxes of matter and energy in arbitrarily defined eco-systems (developed e.g. by Odum, 1983). The machine metaphor (Haken, 1993) stands for the regular input-output behavior of determinate machines which follow clockwork mechanisms. Systems theory has transferred the system metaphor into a set of formal and theoretical methods. Although systems theory originated in information theory and cybernetics, its formal approaches claim universal and interdisciplinary validity (Lilienfeld, 1978).

Environmental sciences regard their object of study as complex natural systems. Different concepts of complexity can be discerned, first, descriptive complexity, second, ontological complexity, third, complex (non-linear) dynamical systems and fourth, an emerging ´complexity paradigm´ replacing the classic, simplifying paradigm (Emmeche, 1997). The notion of ontological complexity is questioned by some researchers, which maintain that complexity has to be conceived as a relation between representation and a represented system (Hauhs and Lange, 1996). Complexity thus is a function of the chosen description, systems which can not be described by a single theory or discipline are regarded as complex (Kornwachs and Lucadou, 1984). Accordingly, the number of different, non-equivalent descriptions of a certain system has been equated with the degree of complexity of the system (Casti, 1986).

Dynamical systems have become *the* formal paradigm in the ´discovery of complexity´ across a range of disciplines: Dynamical systems as universal paradigm propelled the diffusion of complexity concepts in the empirical sciences and have become the leading paradigm for both conceptual and numerical models of complex phenomena. Encoding in a dynamical system is regarded as an adequate way of coping with the (descriptive) complexity of natural systems, allowing for better system understanding and the simulation and prediction of system ´behavior´. Consequently, in the environmental sciences ecosystems are treated, modeled and simulated as (if they were) dynamical systems (see e.g. (Bossel, 1997, Richter, 1994).

Models play an outstanding role in the study, management and utilization of complex natural systems. Models can be differentiated according to the degree of process description, which ranges from indicators to empirical, functional approaches and to mechanistic (stochastic to deterministic), physically based models (Bork and Rohdenburg, 1987, Hoosbeek and Bryant, 1992). Accordingly, three types of models can be discerned (Bossel, 1992): First, behavior-descriptive models, e.g. the growth-and-yield tables of forestry. These so-called empirical, functional and predictive black box models dominate ´utilization technology´ in forestry, agriculture and the management of water resources (Hauhs et al., 1998). Second, elementary-structure models which elucidate determined basic processes. Due to the aggregate description, the parameters of these models lack empirically measurable counterparts and have to be fitted. The Lotka-Volterra equations are an example for this approach (Richter, 1985). Third, mechanistic ´real-structure´ models which make use of supposedly ´real´ empirical parameters. Simulation models in the environmental sciences are elementary- to real-structure models, depending on model purpose (e.g. research models vs. management models; Huwe and Ploeg van der, 1992).

In this paper we focus on mechanistic dynamical models, which simulate biogeochemical processes in ecosystems on a variety of scales. The field of biogeochemical models encompasses models for the behavior and cycling of water and elements, ecotoxicological models and global change models.

Biogeochemical models as scientific products may be regarded from the perspective of prediction or the perspective of understanding, following a debate on the aims of science (Toulmin, 1981). As predictive instruments they are used to simulate the behaviour of complex systems and to compute scenarios of system behaviour under varying external conditions. Examples are the effect of different fertiliser regimes on nutrient losses to the aquatic system, the behaviour of newly created pesticides or the effect of climate change on the terrestrial carbon cycle. On a societal level, models fulfil important roles as management models, as decision support models and in risk assessment studies on different spatial and temporal scales. Dynamical simulation modeling was inspired by and in turn nourished the hope that the environmental sciences would open a way towards environmental engineering (see e.g. Patten, 1994) and the title of the conference proceedings edited by Dubois (1981). The goal was to enable an ecosystem engineer to manipulate natural systems according to societal aims.

In the following, the paradigm of dynamical systems will be characterized, with particular reference to the notions of state and time. We will show how the dynamical system paradigm is adapted in the modeling procedure prevailing in the environmental sciences and we will cast a light on a number of problems arising in the course of the modeling procedure. The paradigm of self-modifying systems is presented as an alternative to the essentialist dynamical system paradigm. Making reference to the two opposing paradigms, fundamental limitations of the dynamical systems approach in the environmental sciences are discussed. Emphasis is on ´noise´ and on the internal production of variables, which can not be accounted for in dynamical systems. In our opinion dynamical models are not suited for the prediction of the future behavior of natural systems. While dynamical models (as products) may play a role as heuristic tools, the modeling process itself can be a way of coping with descriptive and communicative complexity.

2. The dynamical system as a paradigm

The increasing interest in middle-number systems along with the ´discovery of complexity´ in mathematics, physics and the biological sciences (Hedrich, 1994) has found its formal counterpart in the paradigm of complex dynamical systems. Originally a mathematical formalism, it has inspired research in the empirical sciences and has found widespread adoption in ecology and the environmental sciences. "A dynamical system is one whose state changes with time (*t*) "(Arrowsmith and Place, 1994, p. 1, first sentence). The generic system diagram for any continuous dynamical system is shown in Fig. C.1.

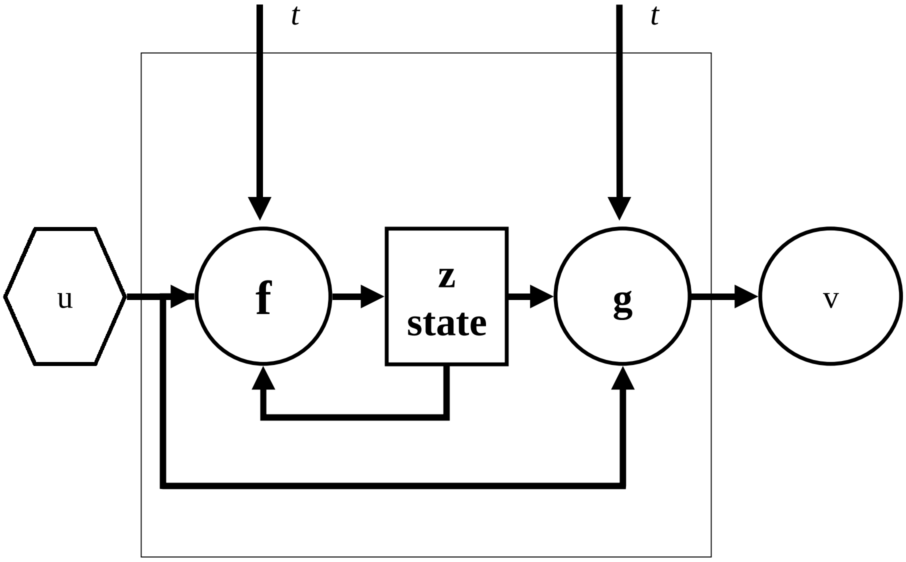

Figure C.1. Generic system diagram for a continuous dynamical system: The general form of the state equations describing the system is: $\partial z/\partial t = f(z,u,t)$ *and* $v = g(z,u,t)$*. z is the state vector, u the vector of environmental inputs, v the vector of system outputs, t the (external parameter) time, f the (vector) state function and g the (vector) output function (adapted from (Bossel, 1997).*

The notion of an abstract system state lies at the heart of dynamical systems: The abstract state is the entirety of all states of a system at a given time. The states of a system are represented by the state variables, which contain all the information relevant to the present of a particular process. The possible states of the system are delimited by an abstract phase space, which has a fixed number of degrees of freedom. The degrees of freedom are defined by the state variables of the system. The system state moves along trajectories in the phase space. In an exo-perspective on the dynamical system, the system collapses to a closed system (Kampis, 1994): The system and its boundaries are defined externally and analytically, closing the system towards its environment except for the vector of environmental input (external variables). The encoding in a dynamical system as a formal set is invariable (first order system). This implies a syntactic conception of information, as pragmatic information would not only change the state but also the structure of the system (Kornwachs and Lucadou, 1984). Fitting into a concept of formal computation (as opposed to e.g. informal, biological and physical concepts; Emmeche, 1994), the system is regarded as a processor of syntactic information, which processes incoming signals according to fixed rules, excluding ´noise´ from the dynamical system.

The temporal dynamics of the system, i.e. the transition from state to state, comes about as the state variables are updated by a transition function. The transition function is a causal-determinate function for a determinate system: If the state of a dynamical system at a certain time is known, the state for any other point in time can be computed. Accordingly, the same transition function can be applied for every interval. Its effect is reversible as the effect of time can always be 'undone' by the application of the time evolution function. In this exophysical concept of time-invariance (Kampis, 1994), time is scalar, invariant, reversible and universal. The underlying notion of time is parameter time (Drieschner, 1996), derived from absolute Newtonian time, which has the following characteristics (Mittelstaedt, 1980, p. 15): Both its topological structure (temporal sequence) and its metric structure (parameter time) are equal. Time has no relationship to objects external to it, while any process refers to the same absolute, universal time (external time).

At the outset of dynamical system building the set for the encoding of the system is needed. The material object under study is not the system, because every material object contains an unlimited number of variables and, therefore, of possible systems. The system is a list of variables (Ashby, 1976, p. 40). The task of the modeler is to vary the list of variables until the system becomes determinate: a determinate machine is one whose behavior can be encompassed in a list of variables that is logically and mathematically workable (Lilienfeld, 1978, p. 37). The basic question is which variables are necessary in order to express a given domain of phenomena (Kampis, 1992a). Modeling is thus faced with a frame problem (Paton, 1996), i.e. the question how reading frames or frames of description should look like (Kampis, 1992a).

Notwithstanding the frame problem, an essentialist notion underlies the dynamical system paradigm: It is assumed that the modeler can discern the essential properties of the represented system. Modelers pretend to isolate "...the essential (behaviorally relevant) system structure, i.e. the identification of essential state variables, their feedbacks, and critical parameters" (Bossel, 1992, p. 264). In this view the dynamical system retains the essence of the represented system, i.e. that which remains the ´nature´ of the system throughout its change from potentiality to actuality. Abstract state and system structure stand for this essence.

3. Ecosystems as dynamical biogeochemical systems?

Ecosystems are constituted from two perspectives (O´Neill et al., 1986, p. 8-13): Firstly, there is the population-community approach, which views ecosystems as networks of interacting populations and in which the environment is regarded as context. Secondly, there is the process-functional approach which focuses on matter and energy fluxes, regarding ecosystems (and compartments) as bio-physico-chemical reactors (see e.g. "the soil as a reactor" by Richter, 1986). Here the function is considered more important than the biotic entities performing it. The circuit and the machine metaphor have been formalized to deal with the biogeochemical perspective on ecosystems.

Biogeochemical models, the focus of this paper, deal with a range of spatiotemporal scales. At one extreme, inputs and outputs of total landscape units (catchments, watersheds) are measured and modeled. At the other extreme, processes such as decomposition or the nitrogen cycle are studied at the point scale. Models for (agro-)ecosystem management and environmental risk assessment deal e.g. with the dynamics of organic matter (Powlson, 1996), the loss of (excess) nutrients such as nitrogen (e.g. de Willigen, 1991, de Willigen and Neetson, 1985, Engel, 1993, Frissel and van Veen, 1981, Groot et al., 1991, van Veen, 1994) and phosphorous (e.g. Cassell et al., 1998), and with the dynamics of organic contaminants such as pesticides (e.g. Calvet, 1995, Richter et al., 1996; Walker, 1995) and other xenobiotics (Behrendt, 1999).

Mechanistic biogeochemical models are encoded as dynamical systems, which are developed in an iterative procedure consisting of the following steps (adapted from Joergensen, 1991 and 1995):

- Definition of problem and bounding of the problem in time, space and subsystems
- Development of model structure
- Sensitivity analysis
- Calibration
- ´Validation´ (conceptual validity)
- Application as scientific or predictive tool
- Validation of prognoses (operational validation)

In the course of model structure development, a conceptual model and mathematical formulations of the processes are developed. For the representation of ecosystems as dynamical systems the problem of system identification, i.e. the identification of state variables, system structure, and the characteristics of the components and the problem of parameter identification have to be addressed (Richter, 1994). The system structure, which connects the elements of the system, is invariable (first-order system). The number of degrees of freedom (variables) is given by the respective system structure. System state and system output of these determinate systems (Fig. C.2) is a function of parameter time and of the:

- initial values of the variables
- parameters of the system
- boundary conditions, i.e. the external variables or driving factors
- temporal transition function of the state variables as a function of parameters and boundary conditions

Characteristic limitations of this modeling procedure are investigated in the following.

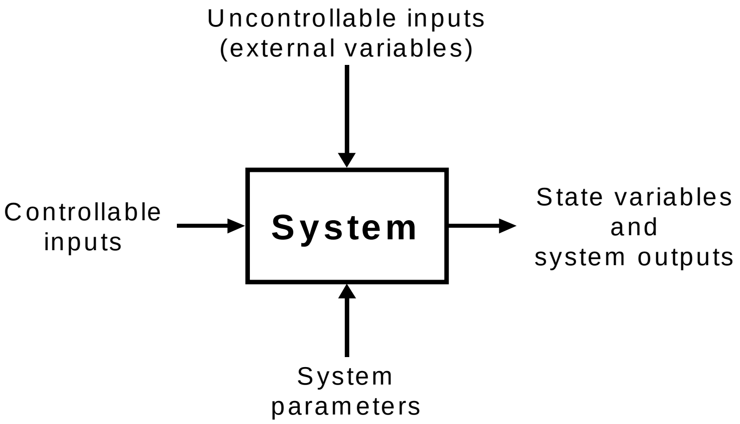

Figure C.2. Characteristics of dynamical systems in the environmental sciences. The system describes the transformation of inputs into outputs and system states under the influence of external driving variables and system parameters (adapted from Berg and Kuhlmann, 1993, p. 4-5 and Gnauck, 1995)

3.1. System structure and processes

Modelers face a basic problem: There are neither theories that allow the construction of models from first principles nor theories that relate observations across different scales (Hauhs et al., 1996). Process descriptions which have been obtained on different but mostly small scales in field and laboratory studies, become the point of departure for model construction: From the variety of processes descriptions, the modeler chooses the ´relevant´ processes to represent a determined domain of phenomena without disposing of *a priori* criteria of relevance nor *a posteriori* criteria to test the selection. Thus modelers tend to base their choice on what from their background of experience seems important, i.e. on prior experience and intuition (Hornung, 1996), putting together what seems relevant to them. Presumably there is an optimal level of model complexity (Wissel, 1989, p. 3), i.e. a point where the degree of model complexity - measured e.g. by the number of state variables - matches data resolution and quality, leading to maximal knowledge gain about the modeled system (Joergensen, 1992, p. 87). However, whether such a point exists indeed and how it is to be found in practice is far from clear. In modeling practice the idea prevails that accounting for more processes leads to more realistic model structures and hence to more accurate models. Environmental systems are regarded as complex, thus "increased complexity in models is interpreted as evidence of closer approximation to reality" (Oreskes, in press). The tendency of putting together as many processes (with their respective parameters) as possible has been termed ´naive modeling´ by Hauhs *et al.*, (1996). It entails the unrestricted increase of degrees of freedom and frequently leads to non-identifiability of model parameters and overparameterization (see below).

3.2. Parameters

In ecology, parameters are coefficients regarded as constant for a specific (eco-)system , p. 67), although in principle no measurable aspect can be considered constant over the observed temporal scales in ecosystems (Hauhs, 1992) due to manyfold feed-backs. Although the application of parameters as constants is unrealistic, the dynamical system approach calls for determined parameter values. Many parameters depend upon internal and external variables and are computed as parameter functions, considered constant for a specific system. For example hydraulic conductivity depends upon water content in a supposedly reproducible way.

Spatial structure is a focal issue in the environmental sciences (De Boer, 1992, Jarvis, 1995, O´Neill et al., 1989, Risser and Box, 1987; Wiens, 1989), as in ecosystems processes in a hierarchy of spatial scales interact shaping a spatially heterogeneous medium (physical structure). The interaction of scale and structure is even more problematic than the non-linearities of the processes. Due to the spatial heterogeneity of ecosystems on all scales, spatial structure is unknowable at any scales of real interest (Beven, 1996). In terrestrial ecosystems, virtually all parameters like the conductance parameters or temperature are spatially distributed. Typical examples are hydraulic conductivities or temperature. For modeling purposes a spatially distributed parameter function has to be computed, which is an arbitrarily distributed continuos-valued function. It is neither constrained by theory (e.g. first principles), nor by *a priori* fixation and it is only loosely restricted by measurement due to variability. The parameter function thus offers enough degrees of freedom to be fitted to any data set, as demonstrated by Figure C.3.

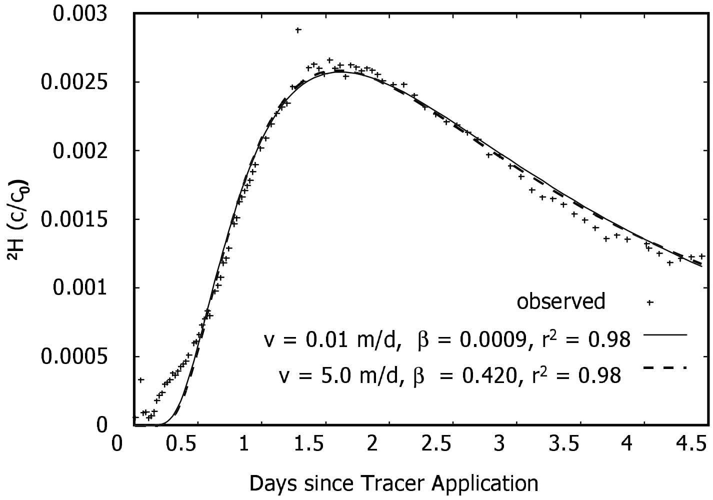

Figure C.3. Breakthrough curve for a Deuterium tracer experiment, together with two different best fits to parameterize a model on soil water movement. The model visualizes the soil as a column containing mobile and immobile fractions of water; ß is the ratio of water contents of the two fractions and v convection velocity. The two degrees of freedom are already too much for a unique solution (from Lange, 1998).

Fitted parameters may allow for adequate reproduction of data from the past, though saying little about the ´correct´ value of the parameter and leaving the issue of parameter identifiability open (Hornung, 1996). Non-identifiability of parameters is a major shortcoming of environmental models.

3.3. Variables and degrees of freedom

In a dynamical system the variables are defined in advance, staking out the phase space of the system. Ecosystems are (stochastic) systems with an infinite number of variables and hence an infinite-dimensional phase space (Lange, 1998). To represent a domain of phenomena, the ´relevant´ variables have to be chosen for the dynamical system. However, there are only subjective criteria of which set of variables is necessary, which set is sufficient and which parts of a set are superfluous to represent a certain domain. Table C.1 describes the different organic matter pools and their parameterization for a specific site used in three simulation models of nitrogen dynamics. The choice of number, size, and kinetic coefficients of the organic pools is "obviously arbitrary" (Richter and Benbi, 1996).

Table. C.1. Characteristics of the different organic matter pools distinguished in three simulation models for agricultural nitrogen dynamics. Parameterization is for a specific site in Denmark (adapted from Vereecken et al., 1991).

Model	Pool	C/N ratio	% of organic C	Half life time
SWATNIT	Litter	8	8-1	693 d
	Manure	10	+/- 1	693 d
	Humus	12	92 - 99	189 y
DAISY	Biomass Pool 1	6	0.28	693 d
	Biomass Pool 2	10	0.04	49.5 d
	Soil Organic Pool 1	11	+/- 80	515 y
	Soil Organic Pool 2	11	+/- 20	10 y
AMINO	Humus	16	99.2	50 y
	Fraction 2	12	< 0.5	77 d
	Fraction 3	58	<0.5	3 y
	Fraction 4	76	0.5	130 d
	Fraction 5	76	<0.5	37 d
	Fraction 6	24	<0.5	65 d
	Fraction 7	24	<0.5	590 d

3.4. Initialization

In the initialization step, the state variables of the system are attributed initial values, making the initial state of the system explicit. Due to ecosystem heterogeneity and measurement problems the actual initial value of a variable can not be assessed. Thus initial values are approximated or chosen arbitrarily, assuming that the system has a short memory and is not sensitive to initial conditions.

3.5. Boundary conditions and external driving variables

Ecosystems are open systems that do not sustain a boundary of their own. Thus ecosystems and their boundaries are defined arbitrarily, i.e. any biotic-abiotic system of interaction can be envisaged as an ecosystem. The choice of boundaries and boundary conditions determines external variables and internal system variables. However, in the practice of field investigation, the precise location of even the analytically defined boundaries is unknown and the assessment of boundary conditions remains vague (Hoffmann, 1997).

Ecosystem boundaries are usually chosen in such a way that physical factors, e.g. weather and climate, become external variables of the system. The external driving variables are assumed to be independent of the respective ecosystem i.e. there is no feedback. They presumably propel the ecosystem which, encoded as a dynamical system, reacts to the external variables in a determinate way.

Future weather and climate conditions can not be known *a priori*, therefore in practice, weather records from the past are used to compute short-term behaviour (Addiscott, 1993). However, past weather records may be unrepresentative of the full range of natural driving forces (Konikow and Bredehoeft, 1992). Particularly when driving forces themselves are subject to major changes (e.g. global climate change) the ´information content´ of weather records is invalidated.

3.6. Calibration

Calibration is the attempt to find the best accordance between computed and observed data by the variation of some selected parameters (Joergensen, 1992, p. 68). However, due to the non-identifiability of parameters and to overparameterization, calibration is a ´fitting exercise´. Therefor it is an open question whether it assures predictive capacity and whether it contributes to understanding (see below).

4. Selforganization and self-modifying systems

Dynamical systems theory has inspired the paradigmatic shift from external organization to self-organization in the empirical sciences (Kratky and Wallner, 1990). In ecology and ecosystem theory the paradigm of self-organization is gaining influence (e.g. Kauffman, 1993, Müller, 1997). Self-organization can be envisaged as an irreversible process leading to complex structures of the system through the cooperative action of subsystems. Several concepts of self-organization have emerged, e.g. cybernetics, autopoiesis (Maturana and Varela, 1980, molecular self-organization (Eigen and Schuster, 1979) and synergetics (Haken, 1990). In most of these concepts self-organization is viewed as a cyclic, recursive process from an exo-perspective. For example an autopoietic machine is defined as "a machine organized as a network of processes of production of components that produces the components which realize the network of processes that produced them" (Maturana and Varela, 1980, p. 78). Cyclic self-organization in which components produce identical or essentially similar components can in principle be represented by non-linear dynamical systems. In contrast to this cyclic conception, *original* self-organization can be visualized by a spiral shifting away from its original position in an adaptive evolutionary process. Original self-organization can be represented by the notion of self-modifying component systems, in which the focus is on incessant (self-)modification. Component systems have the following properties (Kampis, 1992b):

- The set of the different types of the components of the system is open-ended.
- The system produces and destroys its own components during its typical activities.

Due to the production, destruction and *de novo* interaction of components, these systems constantly produce new variables, leading to internal novelty. Sources of internal novelty may be the following (Kampis, 1994):

- Neglected or ´frozen´ lower level variables
- New interactions with the environment
- New contexts
- Change of material properties

Take a pendulum as an example (Fig. C.4): It is encoded as a ´typical´ pendulum swinging back and forth, yet in the course of time new variables of motion keep coming up. Adepts of real-structure models claim that such a model "would be able to predict what would happen if the pendulum were stopped" (Bossel, 1992). The prediction though is only possible, if the potentiality of a stoppage is incorporated *a priori* into the encoding, i.e. if it is accounted for in the reading frame. However, systems pick up information on-line and there is an unlimited supply of things we do not take into account in a given model (Kampis, 1992a), so that it is impossible to map all the relevant properties of the components in advance. Newly produced variables are definable only *a posteriori*.

The validity of the respective set determines the validity of the prediction of system behavior. The encoding of the system in a determined frame of description as in the case of dynamical systems can not give account of the complexity of temporal production of variables (Kampis, 1994), which successively invalidates the set. The time frame is crucial here: While in the short run (as indicated by system times, see below) a given set may predict system behavior with a certain degree of accuracy, in the long run self-modifying systems become unpredictable. The encoded abstract system state is outdated by the production of internal novelty. As component systems are self-referential an external point of reference is lost. The system becomes an endo-system to which an external observer has no access. On large scales the exo-models thus break down.

The notion of time in self-organizing systems is fairly different from time in dynamical systems: External parameter time is replaced by the concept of endo-time or system time. System time is linked to the period of time a system takes before reproducing (Kümmerer, 1996). Hierarchy theory assumes that natural systems can be described in the framework of a nested, constitutive hierarchy (Ahl and Allen, 1996, O´Neill *et al.*, 1986, Müller, 1992). The different levels of organization correspond to different temporal scale levels and to different system times. Accordingly, system times vary from minutes-days (e.g. chemical reactions in soil; molecular level) to months-years (e.g. population dynamics; nutrient cycles) and decades-centuries (e.g. ecosystems, landscapes, global system) (Ulrich, 1993). Symmetry breaking in self-organizing systems (Prigogine et al., 1969) entails irreversibility and the notion of structurally determined systems which depend upon their history.

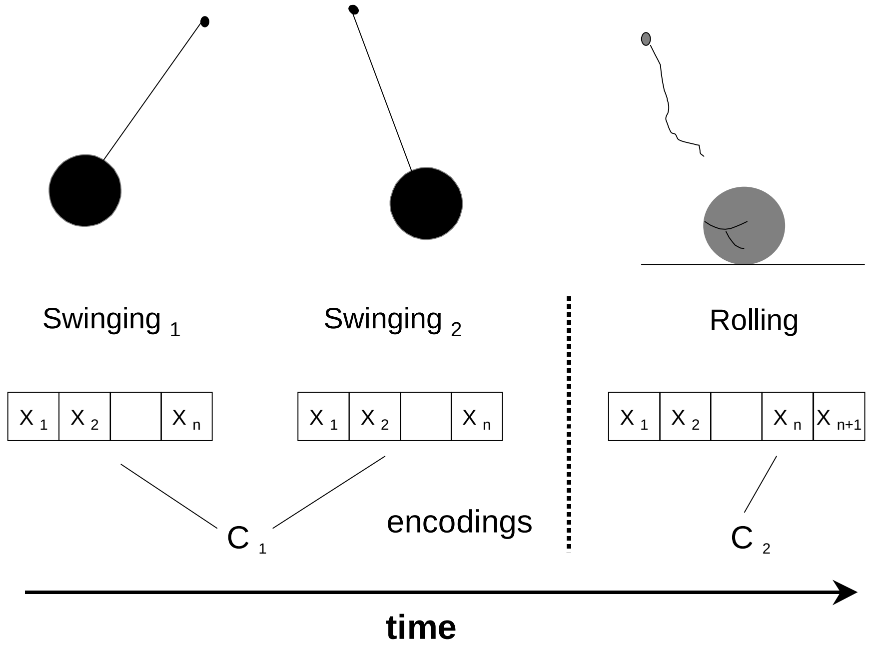

Figure C.4. Encoding of a dynamical system, taking the pendulum as an example. The set of variables (=encoding) on the left side represents the swinging of the pendulum. However, this encoding is not able to account for new variables of motion that keep coming up in the course of time (see the right sight of the figure). New variables thus invalidate old encodings and the system becomes unpredictable (adapted from Kampis, 1994).

The paradigm of self-modifying systems is non-classical, as these systems are:

- Non-determined: In open systems ´properties´, ´states´ and ´objects´ are definable only *a posteriori.*
- Non-local: Objects are context- and time-dependent, are globally dissolved and thus only (*a posteriori* and) globally definable.
- Non-predictable: Internal novelty can not be handled externally, as the advent of new variables invalidates the encoding.

Table C.2 contrasts the two paradigms, the exophysical, essentialist paradigm with its notion of reversibility and the paradigm of self-organization, represented by the endophysical concept of self-modifying systems. Within the essentialist paradigm, properties and states stand for the identity of the system and can be defined *a priori.* Causality is transparent, the ontologically conceived complexity of the system is invariable and the system is computable as properties, states and transition functions are well defined. In ecological modeling a strong notion of essentialism is represented by the "base model", which accounts for the complete input-output behavior of a real ecosystem and which is valid for all frames (Zeigler, 1976).

Table C.2. The classical, reversible, essentialist paradigm of dynamical systems versus self-modification as a model of original self-organisation (compiled from Kampis, 1994 and Paslack, 1991).

	Essentialism (Reversibility)	**Self-modification (Irreversibility)**
Being-Becoming	Properties States	Relations Confluences (potentiality)
Objects	Objects locally and *a priori* definable	Objects globally and *a posteriori* definable (Objects context- and time dependent)
Causality	Transparent Strong Linear	Opaque Weak Non-linear; circular
System	Dynamical systems Analytically defined Given hierarchy Closed	Growing systems Realistically defined Self-created hierachy Open
Complexity	Constant	Variable
Environment	Environment structures system External regulation (external drivers)	Systems structure environment Internal regulation
Time	Scalar, universal parameter time (exo time)	System time (endo-time)
Dynamics/ Development	Reversible trajectories Continuity Regularity	Irreversible Process Bifurcation Singularity
Computability	Computable	Non-computable (Set not definable in advance)

Theoretical ecologist take different positions with regard to the base model concept. While valid real-structure models are supposed to be achievable in principle (Bossel, 1992, Nielsen, 1992) others doubt that such representations can be achieved even for simple real ecosystems (Wissel, 1989, pp. 1-7., Joergensen (1992) acknowledges that such a base model can never be fully *known*, because of the complexity of the system and the impossibility to *observe* all states. In this view, complexity is ontologically conceived and the impossibility of condensing the essence of an ecosystem into a dynamical systems is attributed to practical observational and computational (and not principle) limitations.

In the paradigm of self-modification, ´properties´ must be envisioned in a relational way as they depend on a changing material context. The notion of a system state has to be abandoned, as states require variables as expressions of the properties of the system. The identity and the definition of the system´s components is context and time-dependent and "is only revealed at the end of a process, when all confluences and relations are already known in retrospect" (Kampis, 1994).

Modern natural science is based on an exophysical conception, in which the material system under study is regarded as a sender and the observer as a receiver, collecting the signals emitted by the object. This exo-physical concept collides with the endo-physical notion of self-modifying systems, which pick up and create information on-line and for which limited internal accessibility of information is an ontologically conceived factor (Kampis, 1994). In such systems definitions become temporally changeable due to self-modification; thus the classical concept of computability where everything has to be defined in advance ceases to work.

5. Dynamical systems as analytical tool for ´noisy´ ecosystems?

Systems theory claims to be an interdisciplinary, universal theory, which allows for privileged access to complex phenomena (Lilienfeld, 1978). Dynamical systems as formal, paradigmatic representation of complex systems play an outstanding role in a proclaimed ´structural scientific revolution´ driven by the ´discovery of complexity´ (see e.g. the title of the book by Hedrich, 1994). In the empirical sciences the theory of dynamical systems is important both with regard to the diffusion of complexity concepts and to its application in natural system modeling. The mathematical theory describes the possible behavior of natural systems, only if these systems are adequately represented by systems of partial differential equations. Dynamical systems can only show the behavior prescribed by the mathematical theory, and no other behavior (Hedrich, 1994, p. 30).

The theory of dynamical systems and its application in empirical sciences like ecology and the environmental sciences strives to fit the conception of modern natural science as laboratory science (Hoyningen-Huene, 1989). In the laboratory closed systems are constructed in which if-conditions or antecedents are prepared to produce observable effects or consequents. The corresponding notion of causality is interventionist (Janich, 1992) in that intervention in a specific, controlled setting makes causal relationships appear. According to Vico´s ´verum factum´ principle truth and understanding are attributed only to systems prepared or created by man (Hösle, 1990). Following Hacking, (1992), parts of our environment have to be remade labouriosly into a ´quasi-laboratory´ to reproduce laboratory phenomena. Dynamical systems make use of process descriptions and of parameters established under laboratory conditions, they aim at the exclusion of ´noise´ and they try to achieve a high degree of closure. Thus the theory of dynamical systems attempts to work with the laboratory model and the dynamical system paradigm indeed has been applied successfully to allopoietic, technical systems.

Dynamical systems are *the* paradigm in the environmental sciences, both as a conceptual background and as the formal base of simulation modeling (Joergensen, 1992, Richter, 1994, Richter *et al.*, 1996) although the transferability of system analysis and the paradigm of dynamical systems to ecosystems has been questioned in general already two decades ago (Müller, 1979). For a number of reasons we reckon the dynamical system paradigm inadequate for the representation of ecosystems:

Dynamical systems omit the openness constitutive of ecosystems. Closed dynamical systems run counter to the heterogeneity of ecosystems and to the practical and theoretical limitations imposed on the observation of ecosystems. We agree with the work of Oreskes et al. (1994) who show that ecosystem openness and the formal closedness of dynamical systems collide in three respects: Firstly, dynamical systems require input parameters that are incompletely known (e.g. the distributed parameters). Secondly, they are based on continuum theory which entails a loss of information on structure and processes on finer scales (Oreskes, in press), e.g. the Darcian velocity used for the differential equations is different from the actual velocity at the pore scale. Continuum is a hypothetical idealization, disregarding the discreteness of ecological entities (Breckling, 1992). Thirdly, Oreskes *et al* (1994) show that they recur to additional inferences and assumptions (e.g. kinetic effects are usually neglected), making use of auxiliary hypotheses until the dynamical system and the corresponding simulation model fit the data. Several system structures may produce the same results, i.e. model results are underdetermined by the data.

A dynamical system is an abstraction, in which the system is separated from its environment or background. The background is regarded as noise, which is eliminated in the abstraction step as only well-defined inputs (the input vector) reach the system. The system and its input and output vector become a conceptually closed system. The notion of noise is based on a noise/non-noise difference in conjunction with the system/environment difference introduced by information theory and system analysis. Yet in ecology there are no grounds on which noise (background) and system (abstraction from the background) could be distinguished. Ecosystems and order in ecosystems may actually be the result of ´noise´, thus "noise is music to the ecologist" (Valsangiacomo, 1998, p. 270). In system analysis what started out as an *ecological system* becomes a mere *system* losing its ecological trait: For ecological issues are issues in which an system-environment-*context* is structured due to the development of selective behavior of the system towards its environment. The ecological view of a system-environment-*context* implies unity (of the system-environment difference) despite difference (of system and environment) or even unity due to difference (Luhmann, 1990, pp. 21-22).

The differences introduced to abstract a certain system from its context prevent re-unification and unity of context and environment. For example the reintegration of the population-community difference with the process-function difference is impossible. Correspondingly, ecosystem theory has not come up with a single example of the successful reconstruction or prediction of both aspects of a given system (Lange, 1998).

In dynamical systems a *fixed* number of variables is contained. However, the assumption of a fixed number of degrees of freedom collides with the constant come and go of organisms and the generic innovation and extinction in ecosystems along time, resulting in the production of internal novelty, in the change of system structure and in the creation and extinction of new variables. In our view, ecosystems have to be regarded as self-modifying component systems, for which the *a priori* definition of variables is impossible. Internal novelty and constant drift of ecosystems and their components is not ´noise´, but it is essential for the structural coupling of an open system to its environment (Maturana and Varela, 1987) and for the structuring of the system-environment context, both in the past and in the future. Separation of system and context can at best give a static, momentary view of a frozen system ´state´. Dynamical system modeling of future states assumes that abstract state and external parameter time account for a determinate temporal transition. However, self-modifying systems do not transit from one state with determined properties to another determinate state, but are in an incessant process of original self-organization, in which relations continually are established and lost and states are superseded by confluences. No dynamical system can account for this internal novelty and for the peculiar system times of system components. For short time frames dynamical system descriptions may retain validity. In the long run, however, the dynamical system as a reading frame becomes outdated (Kampis, 1994).

The notion of reversibility underlying the dynamical system paradigm implies that any moment in time is equal and that past states can be computed from present states. The history of the system is supposed to be contained in system structure and specific parameters. Such systems are trivial machines, which are synthetically determined, analytically determinable, predictable and independent of history, i.e. there is an operator relating input to output (Foerster, 1998). However, the failure of simulation models is attributed precisely to the ignorance of the historical character of systems and of system memory (Lange, 1998). It has been hypothesized that sequences in complex systems show non-trivial long-range correlations, entailing a considerable memory effect (Ebeling et al., 1995, pp. 48-50). Historicity denotes the dependence of the present ´state´ of a system upon its history. The notion of historicity corresponds to the notion of non-trivial machines, in which the historical record of operations influences present operations. Non-trivial machines are unpredictable and in most cases analytically not determinable (Foerster, 1998). On top of that, self-modifying systems are not even synthetically determined. Temporal dynamics of self-modifying systems are characterized by symmetry breaking, irreversibility, non-linearity, bifurcations and evolution. From (the discovery of) complexity a path is leading to history (Longo, 1994).

5.1. Validation, validity and future scenarios

The conventional notion of validation distinguishes ´operational validation´ and ´conceptual validity´ (Rykiel, 1996). According to that view, conceptual validity tests the internal logic of a model and says little about the predictive capacities of the model. Operational validation pretends to be an "objective test on how well the model outputs fit the data" (Joergensen, 1991, p. 68-69): Operational validation thus does not imply that the internal structure of the model corresponds to actual processes, but would be the demonstration that a model possesses a satisfactory range of accuracy consistent with the intended application of the model.

However, the conventional notion fails for practical and principal reasons. Generally accepted standards for testing and validating ecosystem models are inexistent. In contrast, current practice is characterized by vague, subjective claims that model predictions show ´acceptable´ agreement with data (Kirchner et al., 1996). Validation procedures commonly consist in the comparison of modeled and measured data or of the outputs of models for the same set of input data. Biogeochemical models for agroecosystems have been validated this way, showing considerable deviation when different model outputs are compared to each other and to measured data (e.g. (de Willigen, 1991, de Willigen and Neetson, 1985, Diekkrüger, 1992). Aside from these practical limitations , there are more fundamental short-comings of the validation procedures in the earth sciences which are discussed by Rastetter (1996). The basal impossibility of the verification and validation of (closed) models of (open) natural systems has been demonstrated by Oreskes *et al*. (1994).

Measured data used for model calibration and validation do not cover the range of potential conditions of system and external variables, particularly as data usually belong to short-term data sets. Accordingly, model validity is restricted to the range of conditions which is represented by the respective data set. When this range is surpassed, the predictive capacity of the model is in doubt and can only be confirmed *a posteriori*, i.e. there is no prediction.

The calibration step, in which models with a large number of non-identifiable parameters (overparameterization) are fitted to measured data, assures that models can be adapted to a given data set, irrespective of the internal structure of the model. Models are not only underdetermined by the data (Oreskes *et al*., 1994), but they can even become immune to the data (Hauhs *et al*., 1996): eventual lack of predictive power is attributed to the ´intrinsic complexity´ of the system under study, leading at best to a readjustment of the model (e.g. by the re-calibration of parameters or the addition of processes). The role of simulation models as predictive tools in the environmental sciences and as instruments of decision support has been harshly criticized for the lack of validity and validation: Mac Lane (1988) speaks of the construction of massive imaginary future scenarios to provide predictions which cannot be verified by checking against objective facts. To him models are speculation without empirical check. Funtowicz and Ravetz (1992) criticize the absence of effective tests for demonstrating what sort of correspondence, if any, there is between models and reality. To them models are devoid of certainty, quality and reality and are to be regarded as a post-modern phenomenon. In the absence of testing, in the minds of their *users* models may take on an aura of reality (Philip, 1991) - a particular precarious point if models are employed as risk assessment tools.

5.2. A role for dynamical simulation models in the environmental sciences?

We claim that mechanistic simulation models of ecosystems are not suitable for predictive purposes, as they are not able to produce non-trivial predictions of future outcomes (Hauhs *et* *al*., 1996). While the mathematical behavior of the formal dynamical system is computable, the ´behavior´ of the natural system is not. Existing data sets or empirically recognized patterns in natural systems may be reproduced by models, but this is not prediction. Non-predictability partly owes to the self-modifying character of ecosystems, which can not be represented by any dynamical system. To embrace the complexity of natural systems (Kay and Schneider, 1995) means to abandon the idea of predictability.

The implications for ecological risk assessment are profound. Unpredictability of natural systems notwithstanding, there still are calls to improve the predictability of biogeochemical system behavior as part of a strategy to reduce global risks, e.g. to decrease the risk of nitrate leaching to the groundwater (WBGU, 1999, p. 323). Nevertheless, there is growing awareness that true predictability can not be achieved. For example Richter (1994) states that the more rapid decomposition of a newly produced pesticide after repeated application may be explained by the adaptive evolution of the microorganisms, but it can not be predicted. The intrinsic unpredictability of ecosystems suggests to follow the precautionary principle in risk assessment (Westra, 1997), instead of succumbing to the ecosystem engineering fallacy.

Yet if dynamical simulation models are not suited for predictive purposes, what role is left to them in the environmental sciences?

We agree with Nancy Cartwright´s statement that models are "a work of fiction" and that "some properties ascribed to objects in the model will be genuine properties of the object modeled, but others will be merely properties of convenience" (Cartwright, 1983, p. 153). In the terms of general modeling theory, the model consists of a set of attributes representing a part of the original and a set of abundant attributes without correspondence to attributes of the original (Stachowiak, 1983, p. 119).

Despite not being a ´real´ thing, "a model may resonate with nature" (Oreskes *et al*., 1994) and thus has heuristic value, particular to guide further study. Corresponding to the heuristic function, Joergensen (1995) claims that models can be empployed to reveal ecosystem properties and to examine different ecological theories. Models can be asked scientific questions about properties. Examples for ecosystem properties found by the use of models as synthesizing tools are according to Joergensen (1994) the significance of indirect effects, the existence of a hierarchy, and the ´soft´ character of ecosystems. However, we agree with Oreskes *et al*. (1994) who regard models as "most useful when they are used to challenge existing formulations rather than to validate or verify them". Models as ´sets of hypotheses´, may reveal deficiencies in hypothesis and the way, biogeochemical systems are observed. Moreover, models frequently identify lacunae in observations and places where data are missing (Yaalon, 1994).

As an instrument of synthesis (Rastetter, 1996), models are invaluable. They are a good way to summarize an individual research project (Yaalon, 1994) and they are capable of holding together multidisciplinary knowledge and perspectives on complex systems (Patten, 1994).

While models as a product may have heuristic value, we would like to emphasize the role of the modeling process: "...one of the most valuable benefits of modeling is the process itself. These benefits accrue only to participants and seem unrelated to the character of the model produced" (Patten, 1994). Model building is a subjective procedure, in which every step requires judgment and decisions, making model development ´half science, half art´ and a matter of experience (Hoffmann, 1997, Hornung, 1996). Thus modeling is a learning process, in which modelers are forced to make explicit their notions about the modeled system and in which they learn how the analytically isolated components of a system can be ´glued´ (Paton, 1997). As modeling mostly takes place in groups, modeling and the synthesis of knowledge has to be envisaged as a dynamic communication process, in which criteria of relevance, the meaning of terms, the underlying concepts and theories and so forth are negotiated. Model making thus may become a catalyst of interdisciplinary communication.

In the assessment of environmental risks, however, an exclusively scientific modeling process is not sufficient, as technical-scientifc approaches to ´post-normal´ risks are unsatisfactory (Rosa, 1998) and as the predictive capacity and operational validity of models (e.g. for scenario computation) is in doubt. The post-normal science approach (Funtowicz and Ravetz, 1992, Funtowicz and Ravetz, 1991, Funtowicz and Ravetz, 1993) takes account of the stakes and values involved in environmental decision making. Following a ´post-normal´ agenda, model development and model validation for risk assessment should become a transscientific (communication) task, in which "extended peer communities" participate and in which non-equivalent descriptions of complex systems are made explicit, negotiated and synthesized. In current modeling practice, however, models are highly opaque and can rarely be penetrated even by other scientists (Oreskes, personal communication). As objects of communication, models still are closed systems and black boxes.

6. Conclusion

The dynamical system paradigm remains within the limits of an exophysically conceived systems theory, which is based on conceptually closed systems and which claims that essential, systemic properties arise from the particular configuration of system components. To achieve closure of dynamical systems, the structure and processes of biogeochemical systems are idealized or simplified, disregarding spatial and temporal variability. Criteria for the identification of essential components, processes and parameters and for their adequate combination in dynamical systems are lacking. Thus the choice of ´relevant´ processes and parameters and the fabrication of system structure are highly subjective. Owing to the impossibility of model validation, models run the risk of losing contact to the empirical ´reality´ they refer to.

In biogeochemical systems, the interplay of biological components with their geochemical environment play a crucial role in the processing of chemical substances. As to this interaction the paradigm of dynamical systems represents only a half-way discovery of complexity: In our view, the closed encoding of ecosystems as dynamical systems runs counter to the self-modifying character of ecosystems as a result of their singular history in a singular context. As stochastic systems (self-modification) in a stochastic context (history), ´complex natural systems´ are unpredictable.

While in the environmental sciences a representationalistic notion of dynamical system models as the product of scientific endeavor prevails, we emphasize the importance of the modeling process. Modeling can be a way of coping with different types of complexity: The complexity of integrating and synthesizing (reductionist) statements and of gluing analytically isolated components; the descriptive complexity that allows for numerous, non-equivalent system descriptions, depending upon standpoint; the communicative complexity, both inter- and transcientific, arising from non-equivalent descriptions of complex systems. Modeling can be a means of the reduction of complexity as it is realizing *one* arrangement (or agreement) amongst innumerous contingent arrangements.

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Diesen "Zivilisationsprozeß" treibt die Flucht
der Technik vor dem Offenen voran.

Peter Sloterdijk - Eurotaoismus

D. WORAUF BEZIEHEN SICH SIMULATIONSMODELLE? REFERENZ, FIKTIONALISIERUNG UND BODENHAFTUNG

Daniel Haag

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D. Worauf beziehen sich Simulationsmodelle?
Referenz, Fiktionalisierung und Bodenhaftung

Zusammenfassung

In diesem Beitrag wird das Verhältnis von Simulationsmodellen als syntaktischen Zeichensystemen zu Ökosystemen als Referenz dieser Modelle untersucht. Es wird illustriert, wie Ökosysteme als dynamische Systeme kodiert werden, d.h. wie ökosystemare Phänomene in ein System syntaktischer Information übersetzt werden und an welchen Punkten dabei der Kontakt zur Referenz verloren gehen kann. Ich diskutiere, inwiefern umweltwissenschaftliche Simulationsmodelle zum Prozeß der Virtualisierung und zum Verschwinden der Realität beitragen und zeige, daß Kongruenz zwischen Original und Modellsystem bei instabilen natürlichen Systemen durch eine Anpassung der Realität an das Modell erreicht wird und nicht, wie bei Simulationsmodellen üblich, durch eine Anpassung des Modells an die Realität.

Abstract

In this paper the relationship between simulation models as systems of syntactic signs and ecosystems as the reference of these models is investigated. I illustrate the encoding of ecosystems into dynamical systems, i.e. the way how ecological phenomena are translated into syntactic systems and how the contact to the reference/original can be lost on the way. I discuss whether simulation models in the environmental sciences contribute to a more general societal tendency of virtualisation and to the disappearance of reality. I argue that for unstable and instationary natural systems congruency between original and model system is achieved through the adaptation of reality to the respective model (intervention), while for simulation models holds the opposite: The model is adapted (´fitted´) to the reality.

1. Einleitung

Ursprünglich als Vortäuschung oder Vorspiegelung[1]mit negativen Konnotationen belegt, hat die Simulation eine erstaunliche Karriere hinter sich. Simulation hat sich als „Problemlösungsmethode, die sich auf das zeitliche Verhalten von Systemen" (Petzoldt 1997)[2] bezieht in den Umweltwissenschaften etabliert, insbesondere weil sie eine "wirklichkeitsnahe, jedoch einfachere, billigere oder ungefährlichere Untersuchung als das Objekt" erlaubt. (Brockhaus-Enzyklopädie 1983). Eine wesentliche Stärke der Simulation liegt mithin gerade darin, daß sie Distanz zum Untersuchungsobjekt, zur ´Realität´ ermöglicht. Simulation als die modellhafte Nachbildung eines beliebigen Systems oder Prozesses durch ein anderes kybernetisches System (Meyers 1993) ist historisch an die „Entdeckung der Komplexität“ (Hedrich 1994) und die damit einher gehende Entwicklung eines theoretischen und informationstechnischen Instrumentariums gebunden. Computermetaphern, Kybernetik und insbesondere die Theorie dynamischer Systeme prägen seither das Bild und die Abbildung von Ökosystemen. Systemtheorie und Kybernetik als syntaktische Artikulationen von Zeichenprozessen, die ohne Bedeutung bzw. Referenz funktionieren (Geier 1999, S. 163) sind mit dem Anspruch angetreten, Erklärungs- und Steuerungswissens für die unterschiedlichsten Systeme zur Verfügung zu stellen (Lilienfeld 1978). Nach einer Phase der Zuversicht, in der danach gestrebt wurde ökosystemare Zusammenhänge mit Hilfe von dynamischen Simulationsmodellen informatorisch und kybernetisch verfügbar zu machen ("ecological engineering", z.B. in Dubois 1981), sind Simulationsmodelle in jüngerer Zeit in die Kritik geraten: Das Paradigma der dynamischen Systeme sei Ökosystemen nicht angemessen (Lange 1998), Simulationsmodelle seien nicht validierbar (Konikow & al. 1992, Oreskes 1998, Rastetter 1996) und gegenüber den gemessenen Daten immun (Hauhs & al. 1996b), es mangele ihnen an empirischem Gehalt, sie hätten spekulativen Charakter (Mac Lane 1988) und könnten allenfalls heuristische Funktionen erfüllen (Oreskes & al. 1994), während sie zu Prognosezwecken untauglich seien (Hauhs & al. 1996b). In gesellschaftlichen Verwendungszusammenhängen, insbesondere beim Risk Assessment, nähmen Simulationsmodelle eine Aura von Realität an (Philip 1991), die simulierte Szenarios u.U. realer erscheinen lassen als Beobachtung und sinnliche Anschauung. So wurden z.B. jüngst die Maßnahmen zur Bekämpfung des Ölteppichs aus der Havarie der "Erika" vor der französischen Atlantikküste allein auf der Grundlage der Prognose von Météo France geplant - ohne den Beobachtungen vor Ort Beachtung zu schenken (Lambel & al. 2000)[3]. Simulationen, die für Laien und andere Wissenschafter opak bleiben (Funtowicz & al. 1992) befördern mitunter das ´Verschwinden der Realität´ (Baudrillard 1982).

Angesichts dieser Kritik, insbesondere an der gesellschaftlich-politischen bzw. planerischen Rolle von Simulationsmodellen, untersuche ich in diesem Beitrag das Verhältnis zwischen natürlichem System als externem Referenten und formalem System als syntaktischem Zeichensystem. Dynamische Systeme, die formalen Systemen gegenüber isomorph sind (Kampis 1991, S.5) dienen als Beispiel. Ich werde fragen, worauf sich Simulationsmodelle beziehen, unter welchen Bedingungen Simulationsmodelle zum "Verschwinden der Realität" beitragen und wie Kontakt und Kongruenz zwischen Modell und externer Referenz hergestellt werden können. Dabei werde ich mich von der These leiten lassen, daß der Bezug zur Referenz einfach zu verlieren ist, während es mühevoll ist, ´Bodenhaftung´ bzw. Kontakt zur Referenz herzustellen.

2. Kodierung und Formalisierung: Dynamische Systeme als Syntax von Ökosystemen?

Ökosystemare Phänomene werden bei der Modellbildung im Zuge eines Kodierungsschritts in dynamische Systeme übersetzt und berechenbar gemacht. Man bedient sich dabei eines Satzes von syntaktischen Zeichen und Verknüpfungen, um Phänomene in numerische und/oder mathematische Aussagen zu übersetzen (Rosen 1991, S. 58-61). In einem Dekodierungsschritt werden Aussagen über das Verhalten des natürlichen Systems aus den Regeln des formalen Systems abgeleitet (Abb. D.1). Dabei kann sich das System nur so verhalten, wie es die Theorie - hier der dynamischen Systeme - vorschreibt (Hedrich 1994, S. 30). Bei Formalisierung und Mathematisierung ist man auf den beschränkten Vorrat an mathematischen Zeichen und Verknüpfungen angewiesen, den die jeweilige Theorie bereitstellt; die Darstellung wird dadurch insofern eingeschränkt, als Gleichungen wegen ihrer mathematischen Eigenschaften und nicht allein aufgrund von Eigenschaften des natürlichen Systems ausgewählt werden (Cartwright 1983, S. 131)[4].

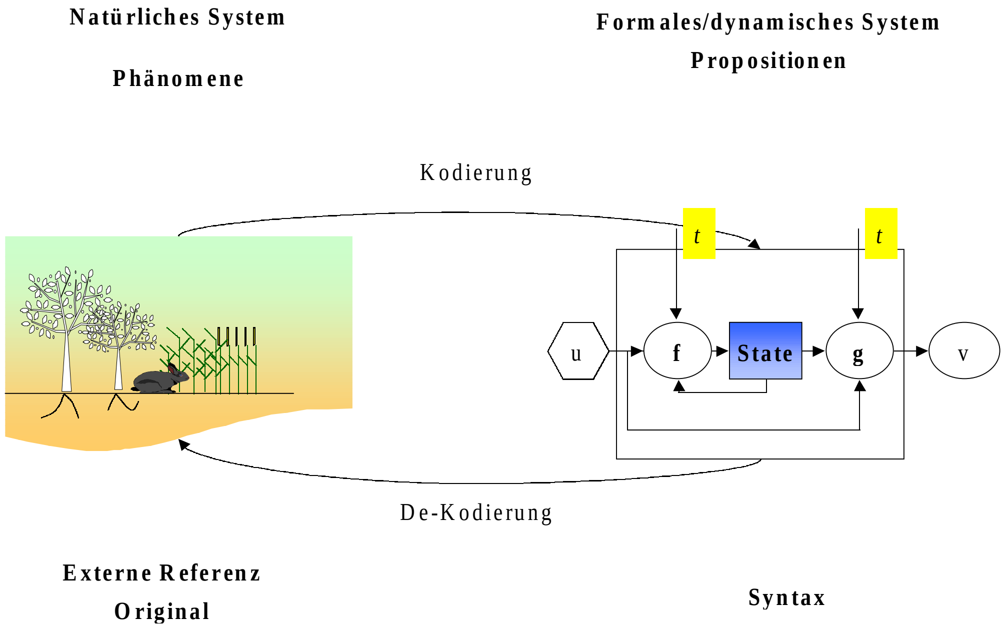

Abbildung D.1.: Übersetzung der Phänomene natürlicher Systeme in ein formales, dynamisches System. Das natürliche System ist die externe Referenz, auf die sich die syntaktischen Zeichen des formalen Systems beziehen (u/v= Vektor der Inputs/Outputs; t = Parameterzeit; f = Zustandfunktion; g = Outputfunktion).

Räumlich-strukturelle Kategorien dominieren die Abbildung von Ökosystemen: Ökosysteme werden als räumliche Strukturen beobachtet, nach konventionalen Kriterien abgegrenzt und im abstrakten Systemzustand (visualisiert als Systemstruktur) des dynamischen Systems repräsentiert. Die im abstrakten Systemzustand fixierten Variablen spannen einen Phasenraum auf, durch den sich das System auf berechenbaren Trajektorien bewegt, angetrieben durch den Parameter Zeit. Zeit entspricht hier der universellen, externen Zeit Newtons, die nicht mit den Phänomenen verbunden ist (Mittelstaedt 1980) und der Zeit Aristoteles als einer Bewegung in einem numerisch abgesteckten Raum (Piettre 1996). Das dynamische System fungiert als Syntax, die die algorithmische Fortentwicklung des Systems von einem früheren zu einem späteren Zeitpunkt vorschreibt (Rosen 1991, S. 279). Dynamische Systeme, die mit der Vorstellung von fixen Eigenschaften, statischen ´Wesenheiten´ (s. u. 3.), abstrakten Zuständen und einer externen Zeit verknüpft sind, stehen für den einen der beiden traditionsreichen Pole "Sein/Werden"[5]. Prozessualen Vorstellungen zufolge wäre dagegen die Identität eines Systems und seiner Komponenten das Ergebnis von sich aktualisierenden Prozessen (Latour 1998, S. 172), von wechselnden Relationen und von "confluences", ´Zusammenflüssen´ (Kampis 1994), d.h. von der kontext- und zeitabhängigen Rekonfiguration des Systems durch das jeweils aktuelle Zusammenwirken seiner Komponenten.

3. Essentialismus: Dynamische Systeme als Wesen von Ökosystemen?

Welcher (An-)Teil von Ökosystemen wird aber im dynamischen System kodiert? Eine Reihe von informationstheoretischen (z.B. System/Umwelt, Rauschen/Nicht-Rauschen) und ökologischen (z.B. biogeochemisch/populationsökologisch) (O´Neill & al. 1986) Unterscheidungen werden an das natürliche System angelegt, um den dynamischen vom kontingenten Teil abzutrennen. Die zumeist binäre Kodierung folgt dem Schema Wert/Rest(-wert), in dem der ausgeschlossene, kontingente Rest durch bestimmte Parameter (z.B. Dispersionskoeffizienten) und durch Kalibrierung eingefangen wird oder als Rauschen und irreduzible "Komplexität" ignoriert wird[6]. Der dynamische Teil wird dann, einer essentialistischen Leitvorstellung (Kampis 1994) folgend, die das "Wesen der Naturdinge" (Hoyningen-Huene 1989) zu erfassen sucht, mit dem Wesen bzw. der Identität des Systems gleichgesetzt. Die Logik der Modellierung ist üblicherweise der Suche nach einer Essenz verhaftet, "the essential ... system structure, i.e. the identification of essential state variables" (Bossel 1992) ist das Begehr.

Abstrakte, digitalisierte Zustände als Essenz von natürlichen Systemen wären in dieser Sicht die natürliche Basis, um "von vielen unterschiedlichen Wahrnehmungen zu einem durch Denken Zusammengebrachten" (Geier 1999) S. 195) zu gelangen, mithin um ´natürliche Arten´ wie etwa Ökosystemtypen zu bestimmen.

4. Konzeptionelle Schließung und die Ausgrenzung der Referenz

Dynamische Systeme und die zugehörigen Simulationsmodelle sind konzeptionell geschlossene Systeme: Das System wird von der kontingenten Umwelt abgegrenzt, die Zahl und Art der Parameter bzw. Freiheitsgrade wird a priori festgelegt und der Systemzustand wird eingefroren (Kampis 1994). Damit verbleibt das System auf der Ebene syntaktischer Information und wird unzugänglich für pragmatische Information, die die Systemstruktur verändern würde (Kornwachs & al. 1984).

Parameter fixieren und schließen das System und ermöglichen die mathematisch-numerische Behandlung des Systems. Diese Parameter und die dem System attribuierten Eigenschaften haben z.T. fiktionalen Charakter, die aus den Notwendigkeiten der mathematischen Theorie (siehe 2.) bzw. der Parametrisierung des kontingenten Teils resultieren (siehe 3.): "A model is a work of fiction. Some properties ascribed to objects in the model will be genuine properties of the objects modelled, but others will be merely properties of convenience ... to bring the objects modelled into the range of the mathematical theory" (Cartwright 1983, S. 153). Konventionale Parameter sind z.B. die Halbwertszeiten für verschiedene Fraktionen organischer Substanz im Boden (Tab. D.1), die sich an mathematisch-physikalische Vorstellungen vom Atomzerfall anlehnen. Konventionale "Rest-Parameter", wie Dispersionskoeffizienten spiegeln die Differenz dynamischer/kontingenter Teil wider. Parameter ohne reale Bedeutung und externe Referenz erhöhen die Anpassungsfähigkeit des Kalküls an gemessene Daten und tragen zur Emanzipation des Modells vom Original und damit zu seiner Fiktionalisierung bei.

Tabelle D.1. Pools organischer Substanz in zwei Stickstoffhaushaltsmodellen. Die Kalibrierung bezieht sich auf einen dänischen Ackerstandort (aus Vereecken & al. 1991).

Modell	Pool	C/N Verhältnis	Halbwertszeit
DAISY	Biomasse 1	6	693 Tage
	Biomasse 2	10	49.5 Tage
	Organ. Substanz 1	11	515 Jahre
	Organ. Substanz 2	11	10 Jahre
AMINO	Humus	16	50 Jahre
	Fraktion 2	12	77 Tage
	Fraktion 3	58	3 Jahre
	Fraktion 4	76	130 Tage
	Fraktion 5	76	37 Tage
	Fraktion 6	24	65 Tage
	Fraktion 7	24	590 Tage

Die Abgrenzung von Innen/Außen bzw. System/Umwelt und Rauschen/Nicht-Rauschen beraubt das Öko-System seines ökologischen Charakters. Während Systeme (im systemtheoretischen Sinn) aus ihrer Umwelt herausgelöst werden, sind Öko-Systeme durch einen System/Umwelt-*Zusammenhang* charakerisiert, also durch Einheit trotz System-Umwelt-Differenz (Luhmann 1990, S. 210). Die Eigenart von Öko-Systemen liegt in der strukturellen Kopplung von System und Umwelt (Maturana & al. 1987, S.85), in der Produktion von Erstmaligkeit (Weizsäcker 1974) und in dem Potential das Fluktuationen (Nicolis & al. 1977) und ´Rauschen´ (Valsangiacomo 1998, S. 270), d.h. die vermeintlich kontingenten Teile des Systems, für die adaptive Anpassung und Ordnung des Systems bereitstellen. Selbstmodifikation von Ökosystemen (Kampis 1991), d.h. die kontinuierliche Produktion und Zerstörung von Variablen steht im Gegensatz zum begrenzten, a priori festgelegten Vorrat von Variablen in dynamischen Systemen (Lange 1998). Ökosysteme sind konzeptionell bzw. epistemisch offene Systeme, in denen on-line[7] Erstmaligkeit produziert wird und neue Kontexte entstehen, die die Bedeutung existierender Systemkomponenten verändern. Wie stark diese Veränderungen auf bestimmte Beobachtungsebenen durchschlagen, hängt z.B. davon ab, wieviel Spielraum Constraints auf höheren Organisationsebenen (z.B. Klima) zulassen. Die Abkoppelung des Systems von seiner Umwelt und von den internen Quellen von Erstmaligkeit führt zur Entkopplung von dynamischem Simulationsmodell und Referenz.

5. Referenz: Worauf beziehen sich Modelle?

Um die Abbildung *eines* Originals konkurrieren unterschiedliche Simulationsmodelle. Zugleich kann dasselbe Modell zur Abbildung verschiedener, konkreter Systeme dienen. Ich skizziere im Folgenden einen Pfad der Fiktionalisierung, der von der Abbildung konkreter Systeme über abstrakte Zustände zur Reduktion auf einen Kalkül führt.

Wenn Simulationsmodelle auf konkrete Systeme mit einer konkreten Geschichte an einem konkreten Ort bezogen werden, haben die Aussagen des Modells zunächst nur Bedeutung für dieses konkrete System. Eine solche Sichtweise kollidiert mit dem Streben nach Universalität und Kontrolle der natürlichen Welt, die an Kontextunabhängigkeit, d.h. die Abstrahierbarkeit von Wissen und Information von der natürlichen Welt und an das Prinzip der Identität durch Veränderung gebunden sind (Merchant 1987, S. 232 ff).

In diesem Sinne wären Simulationsmodelle als Abstraktionen zu konzipieren, die vom spezifischen Kontext unabhängig sind. Die Repräsentation von Ökosystemen durch abstrakte Zustände, die durch eine externe Parameter-Zeit aktualisiert werden, würde diese Systeme theoretisch und praktisch verfügbar machen. Nach dieser Lesart bezögen sich dynamische Simulationsmodelle auf vorgängige ´natürliche Arten´, wie bestimmte Ökosystemtypen oder bestimmte Prozesse (z.B. Stickstoffkreislauf in Ackerböden), die vom konkreten Standort mit seiner Geschichte abstrahierbar wären. Diese Sichtweise steht im Widerspruch zu einer prozessualen Auffassung von Ökosystemen, wie sie von einigen Ökologen vertreten wird. Demnach wären Ökosysteme notwendigerweise als geschichtliche Systeme zu beschreiben (Hauhs & al. 1996a), die nicht auf irgendeine Form von Gleichgewichts- oder

Klimaxzustände zusteuern (Hauhs & al. 2000, Lange 1998, Lange 1999) und die folglich nur schwerlich vorgängigen natürlichen Arten zuordenbar wären.

Aus Abstraktionen erfährt man nichts über das konkrete Verhalten konkreter Systeme. Zwar ließen sich Parametrisierung und Kalibrierung von Simulationsmodellen als Anpassung eines abstrakten Systems an konkrete, lokale Bedingungen interpretieren. Der fiktionale Charakter vieler Parameter macht die Kalibrierung jedoch zu einer bloßen ´Fitting Exercise´, die wenig zum Verständnis und zur Prognose des konkreten Systems beiträgt.

Mit zunehmender Fiktionalisierung werden Simulationsmodelle zu bloßen Kalkülen, die aufgrund ihrer mathematischen Eigenschaften eine hohe Anpasssungsfähigkeit an bestimmte Datensätze aufweisen. Der Anspruch, daß sich das betreffende Modell auf eine empirische Realität beziehe, wird gar nicht mehr erhoben, so z.B. wenn Kastel et & al. (2000) die Verwendung eines bestimmten Ausbreitungsmodells mit den folgenden Worten begründen: "Our choice for this model does not imply that the mobile-immobile model is a valid process model...We choose it merely for its capacity to fit the measured breakthrough curve...". Tatsächlich haben die Parameter in diesem (mit nur zwei Parametern bereits überparametrisierten) Modell keine identifizierbare physikalische Bedeutung (Lange 1998). Hier wird nicht vorgegeben, das Modell bilde reale Strukturen oder Prozesse ab, es geht nur noch um die Auswahl eines geeigneten Kalküls; die Simulation macht sich unabhängig von der Struktur der materiellen Welt.

6. Simulation

Simulationen sind nicht auf die Umweltwissenschaften beschränkt. Im postmodernen Denken von Jean Baudrillard ist Simulation als gesellschaftliche Entwicklungsstufe skizziert worden, in der Zeichenwelten an die Stelle konkreter Realität treten: Zeichenwelten oder Simulationen, die keine Referenz mehr zu Objekten in der Wirklichkeit haben (Baudrillard 1978, S. 14). Baudrillard unterscheidet drei historische Stufen der Abbildung bzw. der Simulakra: Die Repräsentation, die noch vom Prinzip der Äquivalenz von Zeichen und Referent geprägt ist; die Produktion, in der das Zeichen den Referent ersetzt; die Simulation, in der Zeichenwelten entstehen, die über keinen Referenten mehr verfügen (Baudrillard 1982, Baudrillard 1991, S. 17). Simulation ist "jener unwiderstehliche Ablauf, bei dem die Dinge so miteinander verkettet werden, als ob sie einen Sinn hätten, während sie eigentlich nur durch eine künstliche Montage und durch den Unsinn organisiert werden“ (Baudrillard 1994, S. 29). Die Sprache der Simulation ist der Code, "die ´mystische Eleganz des Binärsystems von Null und Eins´" (Baudrillard 1982, S. 91). Binäre Kodierung als alle Repräsentationen leitendes Prinzip folge der "irrwitzigen Illusion, die Welt unter einem Prinzip vereinen zu können" (Baudrillard 1982, S. 93).

Ich teile zwar Latours Kritik an einem Postmodernismus, der jede empirische Arbeit als Illusion und Szientismus verwirft (Latour 1998, S. 65) und für den "alles Trugbild, alles schillerndes Zeichen" ist (Latour 1998, S. 175). Die nicht unübliche Praxis einer Validierung von Simulationsmodellen mit Simulationsmodellen (z.B. Klimamodelle; siehe Rastetter

(1996) für eine kritische Diskussion) und der Einsatz von Simulationsmodellen bei der Entscheidungsunterstützung (Haag & al. eingereicht) lassen es dennoch angeraten scheinen, zu prüfen, ob und wie sich "das geschlossene System...vor dem Referenten" schützt (Baudrillard 1982, S. 117). Fruchtbarer noch wäre es vielleicht nach Vorbildern und Möglichkeiten zu suchen, wie ´Bodenhaftung´ bzw. Kongruenz zwischen Modell und Original/Realität hergestellt werden kann. Auf eine solche Suche begeben wir uns im Folgenden.

7. Anpassung der Realität an das Modell oder Anpassung des Modells an die Realität?

Was die mathematischen Zeichen und Verknüpfungen formaler Systeme und Modelle bedeuten und worauf sie sich genau beziehen ist schwer zu bestimmen (siehe auch die analogen, unfruchtbaren Bemühungen der Begriffsanalyse (Stich 2000). Anders gesagt: "The notion that representations correspond to things, processes or relationships is easy to state but notoriously difficult to justify (Gooding & al. 1989, S. 14). *Daß* sich die Zeichen aber auf etwas Reales beziehen, zeigt sich da, wo Modelle einen erfolgreichen Umgang mit natürlichen Systemen ermöglichen. Vorhersagbarkeit und regelhaftes Verhalten als Bedingungen eines erfolgreichen Umgangs mit natürlichen Systemen sind jedoch an ein stabiles Setting gebunden: "What a system does depends on the setting, and the kinds of settings necessary for it to produce systematic and predictable results are very exceptional" (Cartwright 1999, S. 73). Regelhaftes Verhalten wird durch ein bestimmtes, stabiles Setting, eine „nomologische Maschine“ bewirkt (Abb. D.2), in der bestimmte Komponenten mit bestimmten kausalen Kapazitäten in einer bestimmten Weise verknüpft und angeordnet sind und die gegenüber der Umwelt und ihren Störeinflüssen abgeschirmt ist (Cartwright 1999).

´Von Natur aus´ stabile Settings und ´natürliche´ nomologische Maschinen existieren zwar, so z.B. in der Astronomie, sie werden jedoch nur selten *vor*gefunden. Für ein stabiles Setting läßt sich das Systemverhalten durch bloß phänomenologische oder Korrelationsmodelle - auch ohne oder mit ´falschem´ Realitätsbezug - simulieren und prognostizieren; die babylonischen Astronomie ist ein Beispiel (Toulmin 1981).

Die meisten Systeme und Settings sind jedoch instabil. Dies gilt insbesondere für Ökosysteme, die sich selbst modifizieren und die individuellen Entwicklungspfaden folgen.

Wenn stabile Settings so selten sind, wie kann es überhaupt so etwas wie Prognose und erfolgreichen Umgang mit natürlichen Systemen geben? Die Bedingungen für Vorhersagbarkeit und für einen erfolgreichen Umgang müssen in den meisten Fällen erst fabriziert werden, wie Cartwright (1999), Hacking (1992 & 1996) und Latour (1994) nahelegen. Natürliche Systeme müssen nach dem Vorbild geschlossener Experimental- und Modellsysteme umgestaltet, modelliert werden: "We remake little bits of our environment so that they reproduce phenomena first generated in a pure state in the laboratory." (Hacking 1992, S. 59). Bei der Frage, "*how to transform the farm into a laboratory*" (Latour 1994, S. 249), dienen Modelle als Blaupausen zur (Um-)Gestaltung des Settings; Ziel ist es dabei, eine nomologische Maschine, d.h. ein System mit bestimmten und stabilem Setting herzustellen, die zu regulärem und vorhersehbarem Verhalten führt (Cartwright 1999, S. 58).

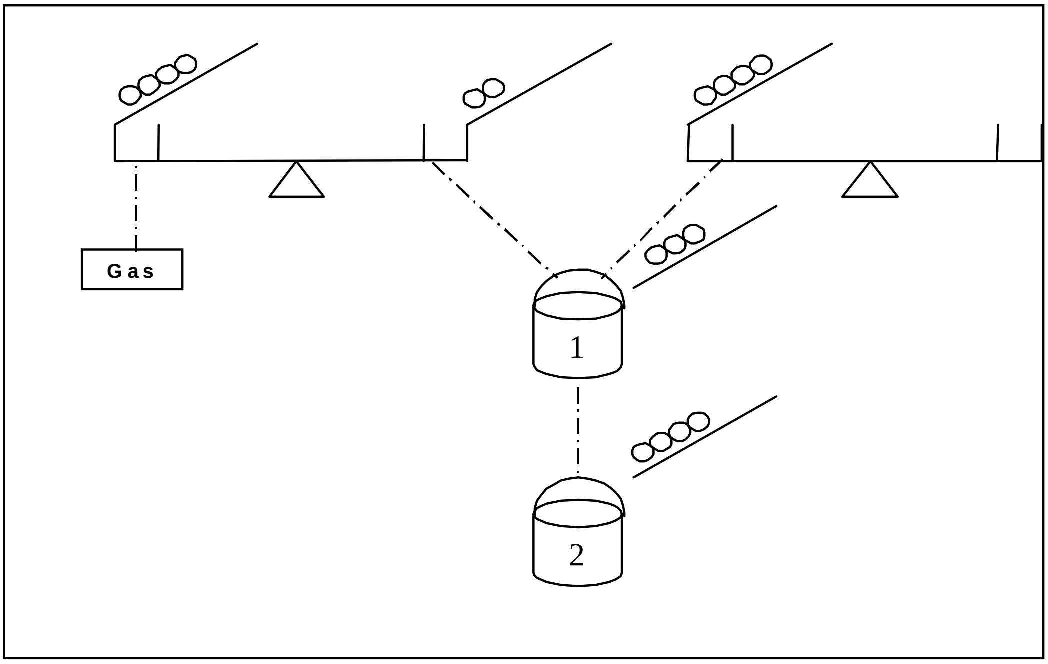

Abbildung D.2.: Nomologische Maschine. Die Verknüpfung bestimmter Elemente mit bestimmten kausalen Kapazitäten führt zu regelhaftem Verhalten. Bei Kenntnis der nomologischen Maschine, läßt sich z.B. die Zahl von Kugeln in Eimer 2 prognostizieren (in Anlehnung an Cartwright, 1999).

Hier spiegeln sich der konstruktive und technische Charakter (Janich 1992, S. 197-213) und das Verum-factum-Prinzip (Hösle 1990) moderner Naturwissenschaft wider, demzufolge Wahrheit und Verstehen nur mit Bezug auf vom Menschen geschaffene Systeme möglich sind. Die Verzahnung von Naturwissenschaft und Technik in der experimentellen Praxis (Hacking 1996) macht naturwissenschaftliches Wissen zu Bewirkungswissen (d.h. zu pragmatischem Wissen, mit dem sich in der materiellen Welt beobachtbare Wirkungen herbeiführen lassen) und Naturwissenschaften zu technischem Know-how (Janich 1992, S. 201).

Simulationsmodelle aber sind schlechte Blaupausen zur Stabilisierung von Settings und zur Konstruktion nomologischer Maschinen. Während Experimentalsysteme auch technisch-materiell geschlossen sind (Haag & al. eingereicht; Radder 1986) und ihre technische Realisation damit vorgezeichnet ist (Hoyningen-Huene 1989), beschränken sich Simulationsmodelle auf konzeptionelle Schließung, haben nur einen geringen Bezug zur materiellen Realität und sind technisch nicht zu *realisieren*. Der immaterielle, untechnische und fiktionale Charakter von Simulationsmodellen macht sie als Blaupausen für den Bau nomologischer Maschinen ungeeignet. Welchen Beitrag sollten z.B. die Parameter aus Tabelle D.1 zur zielgerichteten Intervention in das System und zur pragmatischen

Umgestaltung des Settings leisten? Der mangelnde Erfolg von Simulationsmodellen läßt sich m.E. darauf zurückführen, daß Simulationsmodelle als ´Fitting Machines´ nur lose an die Realität angepaßt werden, während im Falle erfolgreicher nomologischer Maschinen die Realität in einem aufwendigen Prozeß an das Modell angepaßt wird.

8. Schlußfolgerungen

In dynamischen Systemen, die vielen Simulationsmodellen zugrunde liegen, werden Ökosysteme digitalisiert, auf syntaktische Information reduziert und berechenbar gemacht. Es spricht wenig gegen den Versuch, Ökosysteme so zu betrachten als wären sie kybernetische Maschinen und den heuristischen Wert eines solchen Unterfangens zu prüfen. Ich halten es jedoch für kritikwürdig, wenn solche Modelle zu Wesenbestimmungen ihrer Erkennntnisgegenstände erklärt werden. Denn damit wird erstens impliziert, daß dynamische Simulationsmodelle das Original realistisch abbilden. Aufgrund des offenen, selbstmodifizierenden Charakters von Ökosystemen ist dies jedoch nicht der Fall. Zweitens wird suggeriert, daß Simulationsmodelle Prognose und Management und mithin einen erfolgreichen Umgang mit Ökosystemen ermöglichen oder zukünftig ermöglichen werden. Ihre Prognosekraft ist in den unstabilen Settings von Ökosystemen jedoch aus *grundsätzlichen* Gründen begrenzt (Haag & al. 2000) und als Vorbilder zur Konstruktion stabiler, sich regelhaft verhaltender Systeme sind sie nur bedingt tauglich. Wenn Simulationsmodelle zur Entscheidungsunterstützung verwendet werden, so besteht (wie im Fall des havarierten Tankers ´Erika´, s.o.) tatsächlich die Gefahr, daß die Realität hinter die Simulation zurücktritt, wenngleich die Auswirkungen von Entscheidungen, die auf Simulation fußen, höchst real sind.

Die Rolle von Simulationsmodellen verlangt vielleicht nach einer Neubestimmung: Als heuristische Instrumente, als Synthesemethode und als Katalysatoren von Lern- und Kommunikationsprozessen erfüllen sie eine nützliche Funktion bei der Organisation von wissenschaftlichem und nicht-wissenschaftlichem Wissen. Nicht als Repräsentationen, sondern als heuristische Instrumente konzipiert, könnten Sie u.U. einen Beitrag bei der Unterscheidung von stabilen und instabilen Systemaspekten und bei der Suche nach Mustern für stabile Mensch-Umwelt-Interaktionen leisten.

Endnoten

[1] Der Duden definiert ´simulieren´ noch 1963 ausschließlich als "[eine Krankheit] vortäuschen; sich verstellen“.

[2] In der VDI-Richtlinie 3633 heißt es zur Simulation: Nachbildung eines dynamischen Prozesses in einem Modell, um zu Erkenntnissen zu gelangen, die auf die Wirklichkeit übertragbar sind.

[3] Bei Lambel & al. (2000) heißt es im Original: "Hélas, les autorités étaient déjà trop engagées dans une logique où le suivi des prévisions primait sur l'observation". Ich übersetze als: ´Leider waren die Behörden schon zu sehr einer Logik verhaftet, die die Befolgung der Vorhersage über die Beobachtung stellte.´

[4] Ich gehe hier davon aus, daß die Annahme, die Natur spreche die Sprache der Mathematik bzw. *sei* mathematisch, metaphysisch ist. Diese Annahme mag fruchtbar sein und es spricht zunächst wenig dagegen, Ökosysteme z.B. so zu betrachten *als wären sie* dynamische Systeme. Damit ist aber nicht gesagt, daß Ökosysteme ihrer Natur nach durch mathematische Zusammenhänge strukturiert sind.

[5] Bereits vorsokratische Naturphilosophen wie Parmenides und Heraklit zettelten diese Diskussion an, in der Heraklit die Position vertritt, daß die Welt in ständigem Werden begriffen ist und "Zeit ein irreversibler Ablauf wie der Strom eines Flusses". Dagegen glaubt Parmenides, daß jede Veränderung nur scheinbar ist und "Zeit ein reversibler Parameter einer an sich unveränderlichen Welt." (Mainzer 1995, S. 7). Die moderne Dominanz des (platonischen) "Seins" ist ein historischer Zufall (Longo 1994); in jüngster Zeit hat neben Kampis (1991) z.B. Prigogine (1988) versucht das Gleichgewicht zum "Werden" zu verschieben.

[6] Die Abstraktion dynamischer Systeme folgt hier einem physikalischen Leitbild: "Zu jedem Zeitpunkt war die Physik strukturell eingeteilt in zwei grundsätzlich verschiedene Teile: in den dynamischen und in den kontingenten. Zu jedem Zeitpunkt konnte man einen bestimmten Teil der Phänomene durch Gesetze erklären, und der andere Teil blieb einfach übrig als Anfangsbedingung oder freier Parameter." Naturwissenschaft könnte man demnach als diesen "Versuch einer Reduktion von Kontingenz" (Kanitscheider 1999) charakterisieren.

[7] In der Zeit, in der das System kodiert wird, d.h. konzeptionell fixiert und von den Quellen von Neuheit abgetrennt wird (off-line System), läuft das Original-System weiter und produziert neue Variablen (on-line System).

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> Erinnere dich, daß wir manchmal
> Erklärungen fordern nicht ihres Inhalts wegen,
> sondern der Form der Erklärung wegen.
> Unsere Forderung ist eine architektonische.
>
> Ludwig Wittgenstein - Philosophische Untersuchungen

E. PARADIGMEN FÜR EINE NACHHALTIGE LANDNUTZUNG: DYNAMISCHE VERSUS SELBSTMODIFIZIERENDE SYSTEME?

Daniel Haag & Martin Kaupenjohann

in

Flake, M., Seppelt, R., Söngerath, D. (Hrsg.); (1999): Umweltsystemanalyse - Dynamik natürlicher und anthropogener Systeme und ihre Wechselwirkungen, Tagungsband GeoöKon ´99. Landschaftsökologie und Umweltforschung, Heft 33. TU Braunschweig. Seiten 247-250.

E. Paradigmen für eine nachhaltige Landnutzung: Dynamische versus selbstmodifizierende Systeme?

1. Einführung

Ökologie, Ökonomie und Sozialwissenschaften fassen ihre Untersuchungsobjekte in aller Regel als komplexe Systeme auf, zu deren Behandlung auf der Theorieebene *Systemansätze* und auf der Objekt- und Umsetzungsebene *(Simulations-)Modelle* Anwendung finden. Dynamische Systeme dienen dabei als Paradigma zur Abbildung dieser Systeme. Im Rahmen der Debatte um die ökologischen und ökonomischen Dimensionen der "Nachhaltigkeit" (als einem gesellschaftlich-politischen Leitbild) spielen solche Modelle eine wichtige Rolle: Sie dienen der Prognose möglicher zukünftiger Entwicklungen und damit der Abschätzung der ökologischen und ökonomischen Risiken, die aus bestimmten (gesellschaftlichen) Handlungen resultieren. Gerade im Bereich großer (zeitlicher und räumlicher Skalen) scheint uns das dynamische Systemparadigma aber nicht angemessen, sondern ist durch die Vorstellung von selbstmodifizierenden Systemen zu ersetzen, deren Verhalten prinzipiell nicht vorhersagbar ist. Während z.B. bei globalen Umweltänderungen einerseits Unsicherheit und Ungewißheit zunehmen, steigt andererseits zugleich der Einsatz, der auf dem gesellschaftlichen Spiel steht. Ein post-normales Wissenschafts(selbst)verständnis, das die eigenen Beschränkungen anerkennt, scheint solchen Fragestellungen eher gewachsen, als die herkömmliche normale Wissenschaft.

2. Dynamische Systeme

Im Zentrum dynamischer Systeme steht die Vorstellung eines abstrakten Systemzustandes ("state") als der Gesamtheit aller Zustände eines Systems zu einem bestimmten Zeitpunkt. Die Zustände werden repräsentiert durch Zustandsvariablen, die die gesamte für einen Prozess wichtige Information enthalten. Mögliche Zustände werden in einem abstrakten Zustandsraum mit einer definierten Zahl von Freiheitsgraden ("Variablen") realisiert. Die Zeit wird dabei als externer Parameter betrachtet, der mittels einer Überführungsfunktion die Zustände aktualisiert und das System auf eine Bahn (Trakjektorie) durch den Zustandsraum schickt. Zeit wird demnach als skalare, universelle, systemexterne und im Prinzip reversible Größe aufgefasst: Die Wirkung der Zeit kann durch die Anwendung der zeitlichen Entwicklungsfunktion "ungeschehen" gemacht werden, d.h. aus dem gegenwärtigen Systemzustand kann man vergangene wie auch zukünftige Systemzustände errechnen.

Dynamische Systeme lehnen sich damit an ein klassisches, Newton´sches Paradigma an, das ausgeht von einem linearen und starken Kausalitätsbegriff, einer skalaren, universellen Zeit und analytisch definierten, geschlossenen Systemen, die durch externe Faktoren und Randbedingungen gesteuert werden und deren Dynamik durch Trajektorien abgebildet wird

(Paslack, 1991). Die klassischen Prinzipien der Lokalität, Determiniertheit und der Vorhersagbarkeit werden nicht verletzt (Kornwachs and Lucadou, 1984).
Ein solcher Ansatz hat sich als erfolgreich für technische und (manipulierte) physikalische Systeme erwiesen, in denen insbesondere die Zahl der Freiheitsgrade als bekannt und fix vorausgesetzt werden kann.

3. Sind Ökosysteme dynamische Systeme?

In der ökologischen Modellbildung werden Ökosysteme unter zwei verschiedenen Perspektiven konstituiert, einer biotisch-synökologischen und einer abiotisch-biogeochemischen Perspektive (Allen and Hoekstra, 1992). Der biogeochemische "Teil" läßt sich dann als Stoffhaushalt eines Ökosystems in einem dynamischen System abbilden. Besonderes Augenmerk ist dabei auf folgende Punkte zu richten:

- Systemstruktur: Prozessbeschreibungen, die zumeist auf reduktionistischem Wege für kleine Skalen ("Labor") gewonnenen worden sind, müssen in eine Systemstruktur überführt werden, in der Subsysteme und Elemente auf eine ganz bestimmte Weise verbunden sind. Die Auswahl "relevanter" Prozesse und ihre Kombination bleibt dabei dem Modellkonstrukteur überlassen. Die zeitliche Dynamik der Systemstruktur selbst (Systeme zweiter Art) wird i.d.R. nicht berücksichtigt, d.h. die Systemstruktur wird als stabil betrachtet (System erster Art).
- Variablen: Welches Set von Variablen notwendig bzw. hinreichend ist, um einen bestimmten Bereich von Phänomenen abzubilden ist a prior kaum zu beantworten.
- Parameter: Räumliche Strukturen auf verschiedenen Skalenebenen determinieren Prozesse und ihre Parameter (z.B. bevorzugte Fließwege, Leitfähigkeitsparameter, hot spots der Denitrifikation). Die Identifizierbarkeit der Modell-Parameter im realen System ist in einem heterogenen Medium nicht gewährleistet, da eine a priori Identifikation von Parameterfunktionen nicht stattfindet und sich räumlich verteilte Parameterfunktionen durch Messungen nur bedingt eingeschränken lassen. Modelle sind meist überparametrisiert, ihre Kalibrierung wird zur "fitting exercise. Die zur Kalibrierung benutzten Daten entstammen dabei meist kurzen Datensets, die die Spannbreite ökosystemarer Phänomene nicht abdecken (Oreskes et al., 1994). Damit sind Modelle von vorneherein nur innerhalb eines bestimmten Bereichs von Umweltbedingungen valide. Wann dieser Geltungsbereich verlassen wird (z.B. aufgrund extremer Wetterereignisse oder langfristiger Veränderungen) läßt sich nicht a priori bestimmen.
- Anfangsbedingungen repräsentieren den Zustand des Systems zur Zeit t=0. Die Systemgeschichte wird dabei abgeschnitten bzw. in den Anfangszustand, d.h. in die Struktur und die Variablen des Systems verlegt. Sensitivität bezüglich der Anfangsbedingungen ist ein eigenes Problem ("deterministisches Chaos").

Die Annahme einer determinierten Zahl von Freiheitsgraden und einer stabilen Systemstruktur bei der Abbildung von Ökosystemen als dynamischen Systemen ist problematisch: Ökosysteme zeichnen sich gerade durch die zeitliche Dynamik von Freiheitsgraden (Lange, 1998) und Systemstrukturen aus, z.B. durch Zu-/Abgänge von Organismen.

Der jeweilige Modellzweck ist entscheidend für die Validität des Modells (Martin, 1996), insbesondere ist zu unterscheiden zwischen Modellen als heuristischen und als prognostischen Instrumenten (Toulmin, 1981). Dazu korrespondiert einerseits eine konzeptionelle Validierung, die sich mit den Lücken auf der Ebene der ökologischen Theorie konfrontiert sieht, andererseits eine operationale Validierung (Rykiel, 1996), die die prognostische Tauglichkeit überprüft. Die operationale Validierung durch Vergleich mit gemessenen (kurzfristigen) Datensets bzw. mit dem Output anderer Modelle, hat einer Reihe von Modellen begrenzte Prognosefähigkeit attestiert. Langfristige und großskalige Prognosen entziehen sich einer operationalen Validierung, damit werden z.B. globale Klimaänderungen zu einer transwissenschaftlichen Frage (Rastetter, 1996). Eine echte Verifizierung geowissenschaftlicher Modelle ist ohnehin nicht möglich (Oreskes *et al.*, 1994). Wo aber Modelle nur in loser Beziehung zur materialen Welt stehen, besteht die Gefahr, daß die Modelle und ihre Ergebnisse einen virtuellen Raum aufspannen, in dem sich post-moderner Beliebigkeit ohne klare empirische Korrektive entfalten kann. Modelle bilden aber oft die Grundlage für Entscheidungen, die reale Konsequenzen in der "realen Welt" haben (Philip, 1991).

4. Selbstmodifizierende Systeme

Über kurze Zeiträume mag das Paradigma des dynamischen Systems angemessen zur Repräsentation natürlicher komplexer Systeme sein. Betrachtet man dagegen längere Zeiträume (wie im Rahmen von Risikoanalysen), so ist der systeminternen Produktion von Neuheit bzw. Erstmaligkeit (Weizsäcker, 1974) in und der Selbstorganisation von komplexen Systemen Rechnung zu tragen. Als "anschauliches" Paradigma bieten sich selbstmodifizierende Komponentensysteme an, die folgende Eigenschaften besitzen (Kampis, 1992a, Kampis, 1992b, Kampis, 1994):

- Zahl und Art der Komponenten sind im Prinzip unbegrenzt
- Das System zerstört und produziert (auch unter Normalbedingungen) ständig Komponenten

Dadurch werden beständig neue Variablen produziert, die nur *a posteriori* definierbar sind. Kein dynamisches System kann der Komplexität dieser zeitlichen Produktion von Variablen gerecht werden (Kampis, 1994). Charakteristsiche Unterschiede zwischen dem klassisch-essentialistischen Paradigma und dem Selbstmodifikationsparadigma sind in Tabelle E.1. dargestellt. Selbstmodifizierende Systeme sind weder berechenbar noch vorhersagbar. Bei langfristigen Betrachtungen nehmen damit Unsicherheiten und Ungewißheit in erheblichem Maße zu. Diese Ungewißheit ist nicht technischer oder methodologischer (d.h. durch bessere Modelle behebbar), sondern epistemologischer Natur.

Tabelle E.1. Klassisches Paradigma versus Selbstorganisation/-modifikation (in Anlehnung an Kampis, 1994, Müller, 1997, Paslack, 1991, Röling, 1996)

	Klassisch-essentialistisch	**Selbstorganisation**
System	Analytisch definiert, Geschlossen Vorgegebene Hierarchie	Realistisch definiert, Offen Selbsterzeugte Hierarchie
Umwelt	Regelung extern	Regelung intern
Komplexität	Konstant	Veränderlich
"Ontologie"	Eigenschaften Zustand ("state")	Relationen Konfluenzen ("confluences")
Dynamik	Reversible Trajektorie Kontinuität	Irreversiblere Prozess Bifurkation
Kausalität	Stark, linear, direkt Transparent	Schwach, zirkulär, indirekt Opak
Gesetz/Generalisierung	Regularität	Singularität
Zeitbegriff	Skalare, universelle Zeit	Systemzeit (Endozeit)
Epistemologie	Positivistisch/realistisch Privilegierter Beobachter Exoperspektive/-physik	Konstruktivistisch Beobachterperspektiven Endoperspektive/-physik
Wahrheitsbegriff	Objektiv	Pluralität von Perspektiven
Algorithmisierung	Berechenbar	Nicht-berechnenbar
Prognose	Vorhersagbar	Nicht vorhersagbar

5. Post-normale Wissenschaft

In der normalen Wissenschaft werden Probleme in handliche, kleine Teile zerlegt ("puzzle") und einer Lösung zugeführt (Kuhn, 1973). Werte und Normen werden ausgeklammert, "harte" Fakten prägen das Bild. Wenn es aber um umfassendere, längerfristige oder großräumige Weichenstellungen, also um "Nachhaltigkeit" geht, kehren sich die Verhältnisse um: Auf der einen Seite wächst die Ungewißheit und die Fakten werden weich, auf der anderen Seite gewinnen Werte und Normen an Bedeutung und Entscheidungen lassen es an "Härte" gewiß nicht mangeln (Funtowicz and Ravetz, 1991). Die normale Wissenschaft ist mit ihren Mitteln hier hilflos; ein post-normales Wissenschafts(selbst)verständnis (Funtowicz and Ravetz, 1993, Funtowicz and Ravetz, 1991, Westra, 1997) erkennt dagegen die Komplexität der interagierenden natürlichen (Kay and Schneider, 1995) und sozialen System und die damit einhergehende Ungewißheit an. Post-normale Wissenschaft läßt sich wie folgt charakterisieren:

- Das klassisch-essentialistische Newton´sche Paradigma wird durch das Paradigma der Selbstorganisation bzw. der selbstmodifizierenden Systeme ersetzt. Komplexe natürliche (Ökosysteme) und gesellschaftliche System verfügen über das Potential, unterschiedlichen Entwicklungspfaden zu verfolgen, die nicht vorhersehbar sind.
- Ein privilegierter, einzig-objektiver wissenschaftlicher Zugang, weicht einer Pluralität von legitimen, nicht-äquivalenten Perspektiven. Biologische (und gesellschaftliche) Systeme sind insofern komplex, als sie sich nicht mehr durch *eine* Theorie oder Disziplin beschreiben lasssen (Kornwachs and Lucadou, 1984); die Zahl an nicht-äquivalenten Beschreibungen läßt sich als ein Indikator für Komplexität betrachten (Casti, 1986).
- Werte und Normen gewinnen an Bedeutung - auf der Ebene der Beobachtung (die von Theorien und von Interessen geleitet ist), auf der Ebene der Bewertung von Risiko und Ungewißheit und bei der Abschätzung und Bewertung möglicher Handlungsfolgen. Je größer die Ungewißheit wird und je mehr auf dem Spiel steht, desto mehr treten naturwissenschaftlich-technische Zugänge in den Hintergrund, während Wissensansprüche immer auf sozialen Konstruktionen fußen (Rosa, 1998). Wissenschaft wird zum aktiven Partner in der sozialen Konstruktion von Realität (Röling, 1996).

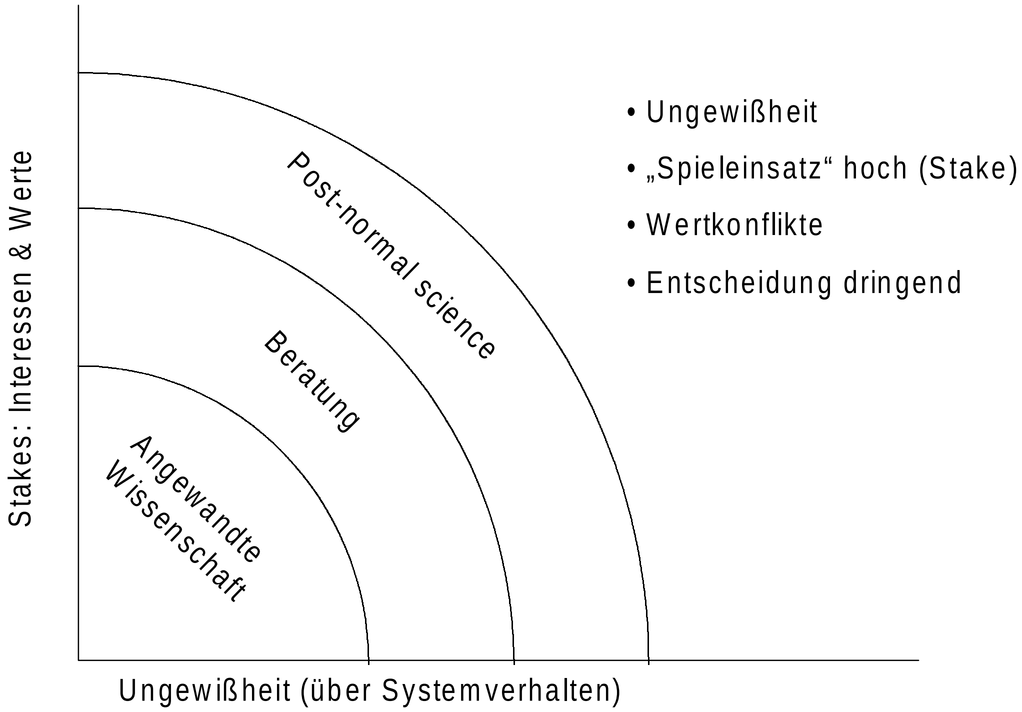

Abbildung E.1. Post-normale Wissenschaft im Verhältnis zu angewandter Wissenschaft und professioneller Beratung (nach Funtowicz and Ravetz, 1991 & 1993).

Die Einbeziehung der verschiedenen Stakeholder in den (wissenschaftlichen) Dialog wird bei post-normalen (und zunächst nur dort!) nötig, die scientific community wird erweitert ("extended peer community") und "demokratisisert". An die Stelle einer instrumentellen und strategischen Rationalität, die die Vorstellung von der (top-down) Diffusion wissenschaftlichen Wissens in die Lebenswelt prägt, tritt eine kommunikative Rationalität (Habermas, 1997, Röling and Jiggins, 1994).

Die Vorstellung, das Verhalten von Ökosystemen auf verschiedenen Skalenebenen zu prognostizieren und nach Maßgabe gesellschaftlicher Kriterien zu regulieren ("Ökosystemingenieur") steht weder im Einklang mit einem solchen post-normalen Wissenschaftverständnis noch mit dem Vorsorgeprinzip (Perrings, 1991, Westra, 1997).

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Fromme Wünsche
Mögen alle Schlüssel doch
Flugs verlorengehen
Und in jedem Schlüsselloch
Sich der Dietrich drehen! -
Also denkt zu jeder Frist
Jeder, der - ein Dietrich ist.

Friedrich Nietzsche - Fröhliche Wissenschaft

Damit ist ferner klar, daß die Wissenschaft an einer Weltkonstruktion arbeitet, die durch ihre Unterscheidungen, aber nicht durch die Welt an sich, gedeckt ist.

Niklas Luhmann - Die Wissenschaft der Gesellschaft

F. PARAMETERS, PREDICTION, POST-NORMAL SCIENCE AND THE PRECAUTIONARY PRINCIPLE - A ROADMAP FOR MODELLING FOR DECISION-MAKING

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Ecological Modelling

In press

F. Parameters, prediction, post-normal science and the precautionary principle
A roadmap for modelling for decision-making

Abstract

In the wake of the "discovery of complexity", dynamical simulation models have become widespread, guiding human interaction with complex systems, e.g. in ecosystem management, environmental decision-making and risk assessment. Any model establishes a reading frame for ecological phenomena or systems, determining the parameters which are assumed to be adequate for the encoding of ecological phenomena. Departing from a definition of observation as the operation of distinguishing and designating and as the application of certain distinctions to complex phenomena, we analyze the construction of reading frames. As dynamical systems are the prevalent paradigm and reading frame for ecosystems, we describe the sequence of distinctions and selections by which scientists encode ecosystems into formal, dynamical system representations. Major shortcomings of the dynamical system paradigm are highlighted: Dynamical systems are conceptually closed systems requiring a fixed set of a priori defined parameters, part of which are parameters of convenience satisfying mathematical needs and part of which are residual parameters which account for noise and system background. Ecosystems in contrast are conceived as conceptually open, self-modifying systems, which constantly ("on-line") produce novelty and new parameters and which cannot be severed from their environment. Although calibration may adapt models to data sets of the past, it does not assure predictive capacity nor validity. While models serve heuristic and theoretical functions and may outline the space of possible behavior, they may be deficient instruments for the reduction of uncertainty as to future system behavior. Different forms of uncertainty are at the heart of environmental decision-making, among them epistemic uncertainty, which arises when the normal, disciplinary forms of uncertainty reduction fail and which leads to debate on adequate ways of coping with uncertainty. Epistemic uncertainty in environmental issues may call for a different type of science that differs from normal, positivist science. Such post-normal science is transdisciplinary, participative and context-sensitive in that it aims at the production of knowledge for concrete, real-world problems. New forms of knowledge production such as the concept of post-normal science in conjunction with the precautionary principle challenge the established authority of science and may lead to an institutional split of science into an academic branch and a managerial, public policy branch. Correspondingly, modelling for theoretical scientific purposes and modelling for decision-making may follow separate paths. Modelling for decision-making may have to take into account requests for transparency and participation ("deliberation frames analysis") and the validity of model products will be judged according to their capacity of providing context-sensitive knowledge for specific decision problems.

1. Introduction

Models guide the observation and representation of ecological phenomena and they guide human interaction with ecosystems. Models of ecological phenomena cover a variety of model types, i.e. mental models (Paton, 1993), material model systems such as mesocosms and mathematical models ranging from statistical to functional and from phenomenological to causal models (Wagner, 1997). A model can be defined as a material or ideal (re-)production of an object by means of analogies realized by a cognitive subject (Ehmke, 1997), emphasizing the role of the observer and the establishment of analogies. The referents of models are systems, or more precisely their structure (Weinert, 1995). Models are more specific than theory in that they make use of a limited set of concrete parameters (Weinert, 1995) and in that they apply to a smaller range of phenomena (Wagner, 1997).

Experimental model systems obey a reductionistic approach in that well-defined phenomena are subjected to controlled experiments which contain a limited number of parameters and which are shielded from the environment (Haag and Matschonat, submitted). Such an activity is in line with the "puzzle" solving of "normal science"(Kuhn, 1973), i.e. the solving of delimited and well-defined disciplinary problems.

Yet as model systems refer to idealized systems with few parameters, their contribution to the understanding of complex emergent systems in which innumerous variables interact is limited (Haag and Matschonat, submitted). The advent of computers and the concomitant paradigmatic change towards complexity in recent decades (Emmeche, 1997; Hedrich, 1994) has made complex systems tractable as computers can simultaneously handle a much higher number of parameters. The rise of systems theory (Lilienfeld, 1978) in its ´analytical´ variant provided the formalisms for the encoding of complex systems (Arrowsmith and Place, 1994; Ashby, 1976; Bennet and Chorley, 1978; Bossel, 1997). Accordingly ecosystems can be encoded into dynamical systems, which attempt to capture the essence of ecological systems.

Dynamical models have become widespread in the environmental sciences, simulating and predicting the behavior of complex ecological systems (Diekkrüger, 1992; Gnauck, 1995; Richter, 1994) and of the interaction of ecological and social/economic systems (Costanza *et al.*, 1993; Underdal, 1997; Underdal, 1998). Dynamical simulation models are employed for all types of environmental prediction, management and regulatory issues (Oreskes, 1998) on all scales, e.g. from the local scale as in models for nutrient (Addiscott, 1995; de Willigen, 1991) or pesticide fate (Calvet, 1995; Wagenet and Rao, 1990) in agricultural soil, to the regional scale as in watershed management models (Young *et al.*, 1989) and to the global scale as in climate change models (Rastetter, 1996). Simulations and scenarios frequently are used in ecosystem management, risk assessment and decision making.

Dynamical simulation models have been criticized in recent years on the grounds that the paradigm of the dynamical system was not adequate for the representation of ecological systems (Haag and Kaupenjohann, 2000; Kampis, 1991; Lange, 1998), and that dynamical models were incapable of non-trivial predictions (Hauhs *et al.*, 1996). As tools in decision-making simulation models were black boxes, opaque to outsiders and would follow an exclusively scientific-technical rationale (Funtowicz and Ravetz, 1992; Rosa, 1998) imposing instrumental rationality in what should be a participative decision process (Renn *et al*., 1995; Stern and Fineberg, 1996b; Webler, 1999).

In this paper we critically analyze the conceptual underpinning of dynamical system modelling and the role of simulation models in environmental science and decision making. Based on the dichotomies of dynamical systems/self-modifying systems (Kampis, 1991) and of normal science/post-normal science (Funtowicz and Ravetz, 1993b), we ask how it is possible to arrive at valid frames of observation for complex systems, i.e. frames which are valid from a scientific perspective (representation function) and a societal perspective (management function). Firstly, we analyze the role of observation in the framing of complex systems, drawing on constructivist systems theory for cognitive (Maturana and Varela, 1980; Maturana and Varela, 1987) and social systems (Luhmann, 1995). Secondly, the sequence of distinctions and selections is described by which scientists abstract and encode ecosystems into dynamical systems. Thirdly, we highlight major shortcomings of dynamical systems and their relation to uncertainty. Fourthly, the conventional "normal" image of science is confronted with "post-normal" issues in which epistemic uncertainty calls for the communicative opening of science. Finally, we depict possible consequences for (simulation) modelling for decision-making which arise from a post-normal image of science.

2. Observation and the construction of reading frames

When constructing models of ecosystems, scientists face a frame problem: specific parameters have to be chosen and some functional or structural relationship between these parameters has to be expressed (Weinert, 1995) to represent a given domain of phenomena. A parameter is conceived here as an objective-real entity or factor, which influences a given material phenomenon causing concrete effects (Franz, 1997). As the term parameter encompasses variables and constants (parameters sensu stricto) and as it depends on temporal boundaries and experimental conditions whether parameter values are constant or vary, we use the terms parameter and variable interchangeably.

The material object under study contains an unlimited number of variables; therefor scientists need to select a list of variables, the system, which accounts for the determinate behavior of the system (Ashby, 1976, p. 40). The construction of a reading frame for a model is not only driven by the system under study, but also by pragmatic features related to the interests of the model builder and the purpose for which the model is built (Stachowiak, 1983, pp. 132).

Prior to observation and distinctions, the world is unmarked, i.e. noise to an observer devoid of distinctions. To observe anything we have to draw distinctions (Spencer-Brown, 1972). We return to this point, when discussing the encoding of ecosystems (see fig. F.1). Observation can be defined formally as the operation of distinguishing and designating (Luhmann, 1994, p. 73). Basic distinctions like identity/difference and system/environment enable self-referential systems to stand out from and to observe their environment. Such systems can be natural systems (e.g. an organism), cognitive systems (e.g. a scientist) or social systems (e.g.

the scientific system), which observe their environment based on distinctions. Thereby observation uses its distinctions as blind spots: It can only see what it can see with the help of these distinctions; it can not see -what it can not see (Luhmann, 1994, p. 85). As we draw distinctions, marked spaces emerge from the original unmarked space. The marked space relegates noise, background and contingent aspects to the unmarked space, a sort of residue which is not further differentiated.

Observing ecosystems scientifically, we apply a series of distinctions ranging from the basic to the specific. The identity/difference and system/environment distinction is the basis for constructing classes of phenomena and of systems such as organisms, populations or ecosystems. More specific distinctions such as producers/consumers or herbivore/carnivore lead to a ever more differentiated model of an ecosystem. Different distinctions and the corresponding blind spots lead to different models of the same material system, e.g. the distinctions of a system ecologist and a population ecologist lead to different system reconstructions (O´Neill *et al*., 1986) which may be incommensurable. The marked space of the system ecologist consists of systems, subsystems, relations, compartments, pools, fluxes etc. and differs notably from the marked space of the population ecologist, who does not even consider ecosystems as systems, but as contingent sets of organisms (Trepl, 1988).

Scientific observation and knowledge have particular features: Firstly, whereas daily life or object knowledge does not differentiate between a statement and its truth, scientific knowledge resides on second order observation, in that what has been observed is not true *per se* but is in turn observed with a true/not-true distinction (Luhmann, 1994). Science thus tries to become aware of its black spots; e.g. when discussing experimental results we focus on black spots arising from the application of a certain method or theory and the corresponding distinctions. Secondly, science has a preference for novelty; new and abstract scientific knowledge does not conform straightforwardly to the requirements of context-dependent decision-making outside the scientific system. Thirdly, the scientific code of truth/non-truth can not be used to select action (Luhmann, 1990, p. 157). Scientific knowledge thus does not aim at action and implementation, as novel knowledge usually is not actionable and, even more important, as the truth of a statement says little about its desirability and applicability to non-laboratory, real-world conditions. The distinctions of science thus are not made to decide how to interact with and manage ecological or ecological-economic systems.

In a functionally differentiated society, numerous societal systems and subsystems exist, which perform determined functions in an exclusive way and which apply specific codes and distinctions; e.g. in the economic system the basic code is solvency/non-solvency and in the juridical system the code is lawfulness/non-lawfulness (Luhmann, 1995). Different codes and sets of distinctions form different perspectives. When it comes to environmental decision-making, different scientific disciplines and different stakeholders or social sub-/systems organize their observation of the environment in accord with their specific codes, distinctions, values and norms, giving rise to non-equivalent or even incommensurable descriptions of complex ecological or ecological-economic systems. Systems have been termed complex in case that a single discipline or perspective does not suffice to describe them (Kornwachs and

Lucadou, 1984). This corresponds to the notion of descriptive complexity, which refers to the relation between an observer and a system (Hauhs and Lange, 1996b). When observing descriptively complex systems the perception of risk becomes multidimensional, value-laden and frame-sensitive (Kunreuther and Slowic, 1996).

3. Encoding of ecosystems into dynamical systems

Scientific observers use specific distinctions to encode natural phenomena and systems into formal systems, i.e. by choosing and formally relating certain parameters. Dynamical systems are the paradigm for the encoding of ecosystems. "A dynamical system is one whose state changes with time" (Arrowsmith and Place, 1994, p. 1). In the following the encoding procedure is illustrated, in which the modeler faces a sequence of decisions, i.e. theoretical distinctions and actual selections among a range of possible selections (Knorr-Cetina, 1991, pp. 26-27).

The original unmarked space is disentangled step by step eventually leading to a highly formal and abstract dynamical system employed as a reading frame for ecosystems (fig. F.1):

Into the unmarked space (fig. F.1a) distinctions are drawn, structuring the ecosystem as to its spatial components. Applying the identity/difference distinction, scientists distinguish entities such as species, life forms or functional groups on the basis of classification schemes. To spatially group and relate entities, compartments such as the root zone or the leaf layer are distinguished (fig. F.1b). Such conceptual models of ecosystems resemble snapshots of the system focusing on spatial or more abstract structures and states. The impact of processes and of time are envisaged as the replacement of structural elements by other structural elements or as exchange operations among the structural elements. Accordingly, it has been claimed that scientists acquire privileged insight into the (spatial) structure of ecosystems; users such as foresters in contrast may have better insight into the temporal evolution of for example a forest stand (Hauhs and Lange, 1996a).

To delimit and close the eco-system conceptually (system/environment-distinction), boundaries are introduced (fig. F.1c). Ecosystem theory advocates boundaries which are based on gradients and on interaction strength, with process rates declining towards the boundaries of a system (Ahl and Allen, 1996; Müller, 1998). Yet according to such a definition every process would require a distinct boundary; therefore boundaries usually are conceived analytically or based on a single criterion (e.g. gradients of potential energy). The definition of boundaries entails the definition of boundary conditions, steering input-output behavior of the system.

Subsystems (e.g. the nitrogen cycle or the water cycle) are defined (fig. F.1d) which account for a closed set of phenomena or processes, which demonstrate a determined input-output behavior (e.g. input of N fertilizer and output of nitrate) and which contain a fixed number of parameters (e.g. different pools of organic matter with different turnover rates). Relations between the different subsystems are defined and subsystems and their relations are linked to specific compartments and their boundaries. Interaction between subsystems and compartments are envisaged as input-output relationships, i.e. matter and energy are exchanged across adjoining boundaries.

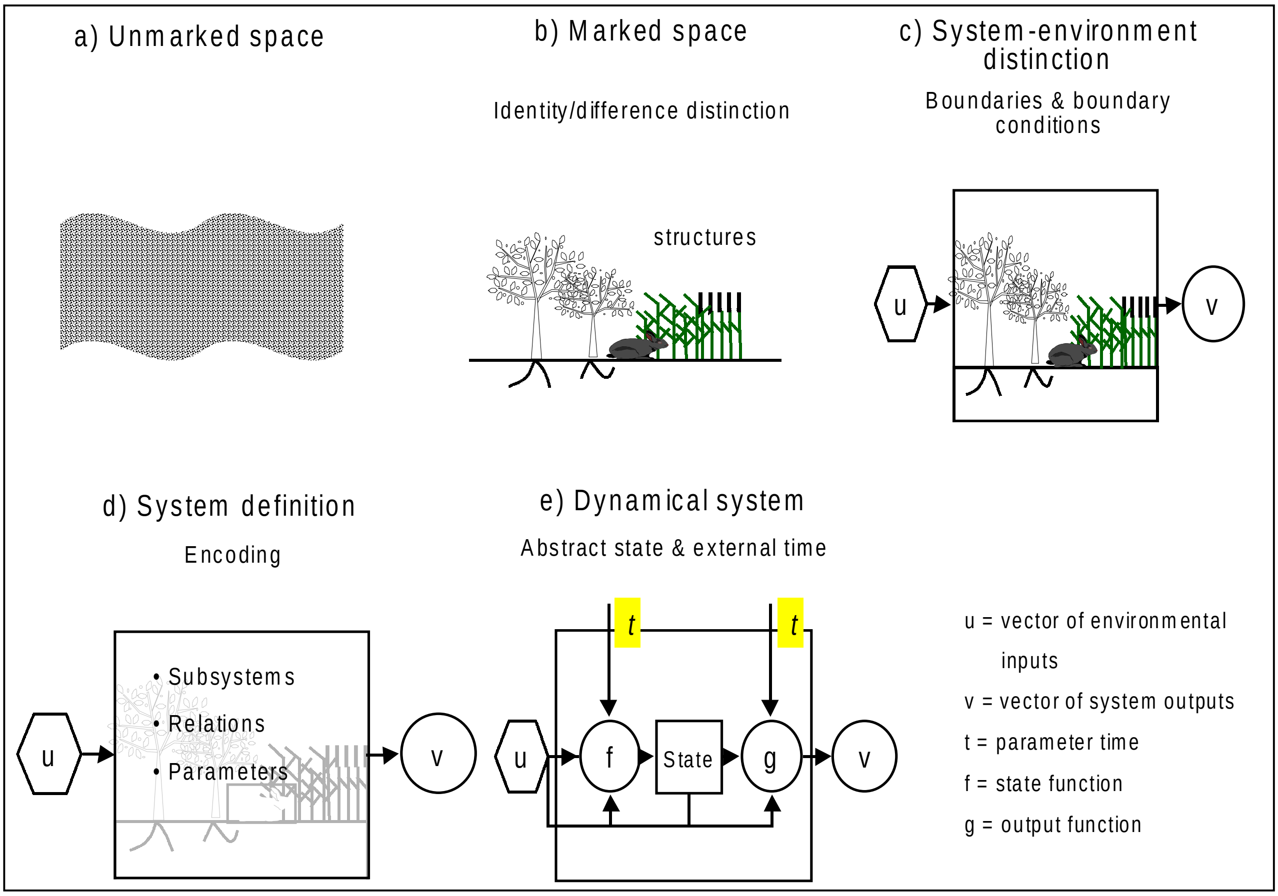

Figure F.1. Sequence of distinctions and selections leading to the abstraction of an ecosystem and its encoding in a formal, dynamical system. For further explanation see the text.

The spatially bounded system is encoded into an abstract state which contains a number of equations and parameters and which is taken to represent the essence of the system (fig. F.1e). The abstract system state encompasses the totality of system states at a given time and incorporates all the relevant information about a process´s present in a state variable (Kampis, 1994). Processes are a function of state variables and environmental input. The state is updated by a transition function in which time serves as a parameter. According to this Newtonian notion, time is universal, invariant, reversible, external and thus detached from the phenomena (Drieschner, 1996; Mittelstaedt, 1980). Owing to the reversibility of time, the effect of time can always be "undone" by the application of the time evolution function (Kampis, 1994). Thus it is assumed that past and future system states alike can be computed if the abstract state is known. After encoding, the behavior of the formal dynamical system can be computed as prescribed by the theory of dynamical systems. These computations are transferred or decoded to the material ecosystem under study and statements as to the behavior of the ecosystem are inferred.

Model building is a subjective procedure, in which every step requires judgment and decisions, making model development ´half science, half art´ and a matter of experience (Hoffmann, 1997; Hornung, 1996). The selections employed in the course of ecosystem abstraction and encoding are subject to criticism precisely because they are selections, i.e. because they include the possibility of alternative selections (Knorr-Cetina, 1981) and hence appear as contingent). Owing to the contingent character of the selections embedded into models, models may face critique from both scientists and laymen, when employed in the course of decision-making.

4. Self-modifying systems versus dynamical systems

Self-modifying systems (Kampis, 1991) have been forwarded as an alternative paradigm to dynamical systems. Self-modifying systems are component system which draw upon an open-ended set of different types of components and which produce and destroy their own components during their typical activities, (Kampis, 1992b). Ecosystems as self-modifying systems produce new variables for example due to the come and go of organisms, due to new environmental contexts, in which hidden phenotypic expressions appear or due to competition or evolutionary processes. As self-modifying systems pick up information on-line (Kampis, 1992a), it is impossible to map all the relevant properties of the components in advance. Thus parameters and variables are definable only a posteriori.

Dynamical and self-modifying systems are opposed in Table 1. The traditional Newtonian paradigm is essentialist (implicit model platonism) and has established a (platonic) preference for ´being´. Classical Newtonian systems are epistemically closed, static ´off-line´ systems whose abstract state remains fixed and untouched by system dynamics and evolution during the run-time of the system. The abstract state can be captured from outside, i.e. from an exo-perspective with respect to the system. The paradigms of self-organization (Krohn et al., 1990) and self-modification (Kampis, 1994) in contrast emphasize process, time and ´becoming´. As systems are self-referential an external point of reference is lost and the observational frame of external observers becomes outdated, as the self-modifying on-line system moves on.

For short time frames the dynamical system approach may be valid, but on the large scale the dynamical exo-models break down (Kampis, 1994). On the time scales targeted by sustainability, ecological systems may have to be conceived as self-modifying systems, as well as the cognitive (i.e. human individuals) and social systems (e.g. the science system) which observe and interact with them .

Table F.1. *The classical, reversible, essentialist paradigm, which dynamical systems refer to versus self-modification as a case of original self-organization (adapted from Haag and Kaupenjohann (2000); cf. Kampis, (1994), Paslack (1991).*

	Essentialism (Reversibility)	**Self-modification (Irreversibility)**
Being-Becoming	Properties States Identity through change	Relations Confluences Potentiality
Objects	Locally and *a priori* definable	Globally and *a posteriori* definable context- and time dependent
Causality	Transparent Strong Linear	Opaque Weak Non-linear; circular
System	Dynamical systems Analytically defined Given hierarchy Closed	Growing systems Realistically defined Self-created hierarchy Open
Complexity	Constant	Variable
Environment	Environment structures system External regulation (external drivers)	Systems structure environment Internal regulation
Time	Scalar, universal parameter time Exo time	System time Endo-time
Dynamics/ Development	Reversible trajectories Continuity Regularity	Irreversible Process Bifurcation Singularity
Computability	Computable	Non-computable (Set not definable in advance)

5. Parameters, prediction and uncertainty

5.1. Parameters in dynamical systems?

As scientists observe the world in terms of parameters, the definition of parameters is critical. Encoding leads to conceptually closed systems as the drawing of a marked space relegates anything but the a priori defined set of parameters to the background of the system. Critique of the dynamical system approach in the environmental sciences focuses on parameters:

- Many parameters are parameters of convenience as parameters are tailored to the needs of the theory: "A model is a work of fiction. Some properties ascribed to objects in the model will be genuine properties of the objects modelled, but others will be merely properties of convenience [...] to bring the objects modelled into the range of the mathematical theory."(Cartwright, 1983), p. 153). Thus parameters frequently lack physical meaning and reference to reality (Haag, in press).

- The set of parameters is closed a priori. Yet ecosystems possess an infinity of parameters and there are no theoretical grounds in ecology to distinguish the system from noise/background (Haag and Kaupenjohann, 2000). Moreover, while the self-modifying ecosystem constantly produces new parameters, no dynamical system can give account of the complexity of the temporal production of variables (Kampis, 1994).
- Time is detached from the ecosystem, linearized and treated as an external parameter in dynamical systems. However, ecosystems organize time internally (system/endo time (Kampis, 1994; Kümmerer, 1996) and ecosystems are historical systems (Hauhs and Lange, 1996a) with non-trivial long-range correlations (Ebeling, 1991), whose record of past behavior determines future behavior (Foerster, 1998).
- To assure conceptual closure of the system, the parameter set is to be complete. Closure, however, is relative to the domain of phenomena of interest and to the theory (Radder, 1986). Thus the choice of parameters is determined by the interests, the theory and the corresponding distinctions of the respective observer. What seems a meaningful parameter to one observer may be irrelevant to another.

5.2. Prediction, validity and reference

The parameter values of a dynamical system have to be calibrated for a specific natural system. As many parameters are parameters of convenience lacking empirical counterparts and as parameters in natural systems are spatially distributed and can only loosely be restricted by measurement (Lange, 1998), models offer a high number of degrees of freedom for calibration: Accordingly, models can be adjusted to data sets of the past. However, calibration does not ensure predictive capacity: No data set can represent the range of naturally occurring conditions (Konikow and Bredehoeft, 1992), so that the model is left in the limbo, when the natural system leaves that range. Any observer´s domain of experience encompasses only a small window of possible events, from which it is difficult to induce future events (as in predictive modelling). Take Russel´s chicken as an illustration of the imminence of surprise: The chicken waits eagerly for the farmer, who comes to feed her first thing in the morning - until the unexpected day that he comes to chop off her head. In ecology, the setting of a system may change as easily, partly invalidating past observational data with respect to their predictive capacity. In other words: "What a system does depends on the setting, and the kinds of settings necessary for it to produce systematic and predictable results are very exceptional" (Cartwright, 1999). Self-modification may change the setting and lead to fundamental non-predictability, as in the course of time the reading frame of the dynamical model may be invalidated as new variables emerge in the real-world system.

Dynamical simulation models have accordingly been criticized for lack of empirical check (Mac Lane, 1988), lack of reference to reality (Haag, in press), lack of predictive capacities

(Hauhs et al., 1996; Oreskes, 2000; Oreskes et al., 1994) and lack of transparency (Funtowicz and Ravetz, 1992). Effective tests for demonstrating what sort of correspondence there is between model and reality are argued to be absent (Funtowicz and Ravetz, 1992) and it is claimed that it is impossible to validate models for principle reasons (Konikow and Bredehoeft, 1992; Oreskes, 1998; Oreskes et al., 1994; Rastetter, 1996). While simulation models may lose and loosen contact to reality (Baudrillard, 1991; Haag, in press), the consequences of decisions based on such models are real.

Opposing a predictive role for dynamical simulation models Haag and Kaupenjohann (2000) agree with Oreskes et al. (1994) that simulation models are heuristic tools that may "resonate with nature". Models have theoretical value as they can be used to reveal ecosystem properties and to examine different ecological theories (Jørgensen et al., 1995) and can be asked scientific questions about properties (Jørgensen, 1994).

Simulation models produce statements rather on possible but not on actual system behavior (Caswell, 1988), i.e. they outline a space of possibles or of potentiality; herein lies an unparalleled strength of simulation modelling. The realization of specific states within this space is uncertain, resembling the situation in the laboratory sciences: Employing closed systems which are shielded from the environment, scientists assess capacities, e.g. the capacity of aspirin to relieve headaches (Cartwright, 1994), but whether this capacity is actually realized in an open, concrete real-world system, i.e. whether aspirin actually relieves today´s headache, is beyond anticipatory scientific knowledge. Although the future behavior of ecological systems remains uncertain, humans constantly have to decide on how to actually interact with concrete systems.

5.3. Uncertainty and models

Simulation models can be conceived as instruments for the reduction of uncertainty as to the behavior of ecological systems. Scientific uncertainty may be classified as (a) data unavailability, (b) ignorance, i.e. the fact that scientific evidence cannot be generalized and (c) indeterminacy, i.e. the fact that the parameters of the system are unknown (O'Riordan and Jordan, 1995). Simulation models relate to this classification of uncertainty as follows:

- Data unavailability: Simulation models frequently are used to make up for lacking data; yet the reference to reality and the validity of model outputs cannot be verified.
- Ignorance: Simulation models like any models face a trade-off between generality and concrete significance, i.e. either they refer to specific systems with a specific setting and history, entailing little for the general case or they are abstract general models entailing little for the specific case (Cartwright, 1983).
- Indeterminacy: Whether the selection of parameters for a dynamical model is valid for the domain of phenomena of interest it was intended for or for other domains cannot be stated a priori. Self-modification may further reduce validity in the course of time.

Another classification of uncertainty distinguishes technical, methodological and epistemological uncertainty (Funtowicz and Ravetz, 1993a). Technical uncertainty can be remedied by a better conceptual and material closing of experimental systems (Haag and

Matschonat, in press). Uncertainty as to which methods are adequate still revolves around the question by which means true knowledge can be achieved. In epistemic debates, however, not the truth of statements is at stake but the plausibility of conflicting knowledge claims (Schomberg, 1993). In a situation of epistemic uncertainty analogies from well-known areas of research are invoked, but as the principles and paradigms of these areas differ there is no common ground as to the way how new knowledge to reduce uncertainty is to be acquired. Environmental decision-making frequently confronts issues of epistemic uncertainty, take e.g. the debate on genetically modified organisms in which ecologists and molecular biologists resort to their specific disciplinary principles, analogies and models to make up for lacking anticipatory knowledge (Kolek, 1993; Schomberg, 1993). On which paradigms simulation models should be based and whether simulation models are valid instruments at all becomes a matter of epistemic debate in such environmental issues.

6. New forms of knowledge production to address uncertainty?

6.1. Normal science versus post-normal issues

When simulation models are used to address real-world decision and management issues such as large scale pollution, watershed management and climate change they are faced with problems that differ considerably from the well-defined problems addressed successfully in the framework of normal, positivist science producing knowledge in "Mode 1" (Gibbons et al., 1997). Mode 1 aims at universal, objective and context-free knowledge and has led to a complex association of ideas, methods, norms, practices, instruments and institutional conditions. Scientific disciplines which are characterized by cognitive and social hierarchies are its basic units. Knowledge production in Mode 1 usually shares the following positivist positions and assumptions with normal science: Firstly, the world divides into facts and phenomena, making nature capable of reductionistic, mathematical explanations. Secondly, the perception of phenomena is and must be independent of values, norms and goals. Thirdly, systems are to be studied which are "highly abstracted and idealised replicas of phenomena, being characterizations of how the phenomena would have behaved had idealised conditions been met." (Weinert, 1995). Messing with real-world systems outside the laboratory is unwarranted.

In contrast, post-normal issues (Funtowicz and Ravetz, 1993b) deal with ill-defined problems (Scholz, 1997) in concrete, entangled and complex economic-ecological systems, frequently involving local-global interactions, large scales, broad scopes and a high degree of uncertainty of all kinds, notably epistemic-ethical uncertainty: The traditional opposition of "hard" facts and "soft" values is inverted as here decisions are found that are "hard" in every sense, but for which the scientific inputs are irremediably "soft" (Funtowicz and Ravetz, 1991). The observation and description of post-normal issues cannot be severed from the perspective of the observer or the observer´s values and norms; different perspectives, domains of phenomena of interest and decisions stakes lead to differing, non-equivalent system descriptions.

6.2. The precautionary principle

For post-normal issues, frequently the precautionary principle is invoked. The precautionary principle has four dimensions, (a) the threat dimension, (b) the uncertainty dimension, (c) the action dimension and the (d) command dimension and can accordingly be phrased in general form as follows: "If there is a threat, which is uncertain, then some kind of action is mandatory" (Sandin, 1999). Normal science is not competent as to these dimensions, because it (a) excludes values and thus threats from its realm, (b) trains for the exclusion of uncertainty by establishing closed systems but not for communicating and managing uncertainty in open systems and (c) has no code/distinctions for the selection of action nor (d) for their justification. Thus the precautionary principle challenges the established authority of normal science, calling for a different type of science.

6.3. New forms of knowledge production

Normal knowledge production according to Mode 1 contrasts with an emerging way of knowledge production, Mode 2, encountered, envisioned and called for in the environmental sciences and areas such as technology assessment, climate, risk and sustainability research. Knowledge production in Mode 2 takes place in heterogeneous contexts of concrete applications, framing and solving problems for concrete and local contexts (Gibbons et al., 1997). It involves transdisciplinarity (Gibbons et al., 1997; Nowotny, 1999) disregarding disciplinary methods, hierarchies and boundaries. The concept of post-normal science (Funtowicz and Ravetz, 1992; Funtowicz and Ravetz, 1993b) is akin to Mode 2 production of knowledge. Post-normal science has to cope with the framing of complex systems under conditions of uncertainty and perspectivity. Post-normal science comprises three aspects, (a) the increased relevance of values, (b) the switch from the traditional Newtonian paradigm to self-organization (Tab. 1) and (c) the recognition of the indeterminacy of ecosystem development (Westra, 1997). It differs from normal science particularly concerning epistemology and the way how scientific (sub-)systems (e.g. disciplines) are closed and secluded from other scientific and social systems (Tab. 2). Extending the concept of post-normal science leads to a managerial conception of science in which skills and judgement become important (Funtowicz and Ravetz, 1993a; Nowotny, 1993). New forms of knowledge production such as strategic research, post-normal science and Mode 2 converge in the following points:

- Transdisciplinarity (Jaeger and Scheringer, 1998; Nowotny, 1997): Real-life/real world problems instead of isolated disciplines drive the definition and delimitation of issues. Methods are tailored to real-world problems instead of adapting the problems to disciplinary boundaries and methods.
- Non-equivalent descriptions: There is no privileged epistemic access to complex systems that would allow for a single, objective description; instead different perspectives lead to a plurality of legitimate system descriptions which cannot be reduced to a common denominator (relativity of parameter selection; epistemic debate, endo-perspectives).

- Management of uncertainty and extension of the peer community: While normal science disposes of common standards of quality and of validation, in a situation of epistemic uncertainty the quality and validity of scientific results becomes a matter of debate (Schomberg, 1993). Stakeholders from different scientific disciplines and from the ´lay´ public participate in quality control, which leads to the democratization of science (Funtowicz and Ravetz, 1994; Röling and Jiggins, 1994). "Quality control can no longer be performed by a restricted corps of insiders [...] Knowledge of local conditions [...] can also determine which data is strong and relevant" (Funtowicz and Ravetz, 1993a), particularly as scientists are trained to abstract and generalized conceptions (decontextualization). Scientists should communicate uncertainty and the quality of data to decision-makers (Costanza et al., 1992). This holds particularly for the output of simulation models, as in the minds of their users, simulation models may acquire an "aura of reality" (Philip, 1991), and actuality, although they may only outline a space of possibles.
- Participation and communicative rationality: Following the guideline "deliberation frames analysis - analysis guides deliberation" established by the U.S. National Research Council for risk issues (Stern and Fineberg, 1996) deliberation and discourse among stakeholders serve to identify phenomena and parameters of interest, to formulate problems and to frame observation. Methodological foundations for stakeholder participation have been laid in recent years (Renn et al., 1995; Stern and Fineberg, 1996; Webler, 1999), mostly referring to discourse ethics (Kettner, 1993).While the instrumental and strategic rationality of normal science assumes a top-down diffusion of scientific knowledge into the "Lebenswelt" (i.e. the real-world), communicative rationality (Habermas, 1997; Röling and Jiggins, 1994) emphasizes discourse and negotiation. Knowledge claims as to socio-ecological complex systems and the pertaining risks are regarded as dependent on social constructions (Rosa, 1998). #
- Precautionary principle: Action in advance of scientific proof but in accord with stakeholders' vital interests is warranted (Perrings, 1991; Westra, 1997).

New forms of knowledge production would play an active role in the construction of frames of observation for sustainable ecosystems.

Table F.2. *Normal, positivist science versus post-normal science (compiled and adapted from Funtowicz and Ravetz, 1993a; Funtowicz and Ravetz, 1993b; Nowotny, 1999b; Röling, 1996; Röling and Jiggins, 1994).Differences mainly attain epistemology and the closure/opening of scientific (sub-)systems towards other scientific subsystems (e.g. disciplines) and society.*

	Normal science	**Post-normal science**
Epistemology	Essentialist	Constructivist
	Exo-perspectives	Endo-perspectives
	Abstraction	Context
	Universal knowledge	Reconfiguration of knowledge in context (local)
	Regularities	Singularities
	Objective scientific truth	Plurality of perspectives
	Single description	Non-equivalent descriptions
Rationality	Instrumental/strategic	Communicative
Methods	Disciplinary	Transdisciplinary
	Established; universal	Problem-driven; specific
Peer community	Closed expert system	Extended peer community (Stakeholders)
Quality control	Disciplinary	Transdisciplinary
	Universal	Context-specific
Problems/issues	Puzzles	Ill-defined issues
	Disciplinary definition	Real-world formulation
	Analysis frames deliberation	deliberation frames analysis
Uncertainty	Technical	Epistemic
	Low	High
Risk	Scientific-technical	Social construction
Stakes	Low	High

7. Towards Context-sensitivity: Post-normal modelling?

Conventionally, simulation models for risk assessment and decision-making follow a scientific-technical rationale and are opaque to outsiders, whether other scientists or the public (Oreskes, pers. com.). Modelers select the phenomena and parameters they regard as relevant, ignoring the perspectives of other observers and modelers decide on the validity and applicability of models. Such practice accords with Mode 1 production of knowledge (Gibbons et al. 1997) and is justified if models are intended as theoretical or heuristic instruments. If models are conceived for decision support, however, science leaves the confines of academia and becomes managerial science, which is "no longer immune from society"; thus two types of science may come into co-existence: "An institutional split [...] is likely to occur within the sciences - between a public policy branch and an academic branch."

(Nowotny, 1993). Environmental modelling may perform a similar split into a public policy branch and an academic branch.

"Managerial modelling" should in our view be guided by new forms of knowledge production, in which stakeholders participate in the framing of systems ("deliberation frames analysis"). The choice of the domain of phenomena of interest, of the adequate theory and of the parameters and the selection and evaluation of models for decision purposes thus would be the task of an extended peer community operating in and for local contexts. Dynamical models offer a remarkable potential for consensus building in concrete environmental decision situations (Costanza and Ruth, 1998).

7.1. Validation as the establishment of legitimacy?

Some form of environmental forecasting is certainly necessary as in the "extended present" we are living in, humans dispose of and partly predetermine the future already in the present, reducing future degrees of freedom (Nowotny, 1995) . Notwithstanding, we do not agree with the notion that models can be used for prediction in a literal sense, as simulation models lack predictive capacity for real-world systems and cannot be validated (for an in-depth discussion of validation see Haag and Kaupenjohann (2000), Konikow and Bredehoeft (1992) and Oreskes et al. (1994).

The original meaning of validation is not necessarily the establishment of truth but of legitimacy, typically given in terms of contracts and arguments (Oreskes et al., 1994). In the face of the impossibility of operational and conceptual validation, some modelers conceive validation as a transscientific requirement (Rastetter, 1996). Validation thus becomes a negotiation process, in which criteria of validity are negotiated corresponding to the uncertainties, stakes and interests involved. In accordance with the precautionary principle, forecasting would become a matter of public negotiation, of arrangements between ´best guess´ predictions and social weightings of agreed criteria (O'Riordan and Jordan, 1995). Interaction with the ecosphere is a risky endeavor, in which risk can be conceived as a game in which the rules must be socially negotiated within the context of specific decision problems (Kunreuther and Slowic, 1996). Consequences arising from this for the framing and transparency of models and for the communication of uncertainty may be guided by the principles of the new production of knowledge.

7.2. Recontextualization

Since early modern times science strives for universality and control of the world, which are tied to context-independence, i.e. abstractability of knowledge and information from the natural world, and to the principle of identity through change (Merchant, 1987). In contrast, knowledge production in Mode 2 ceases to define reliable knowledge in a universalistic sense, but becomes tied to a particular context. It is argued that if science is to avoid becoming stuck in the objectivity trap, it has to develop greater context-sensitivity (Nowotny, 1999). Societal contextualization of knowledge implies that reliable knowledge will be tested not in the abstract, but under very concrete and local circumstances. (Nowotny, 1999). Thus scientific models have to be evaluated for specific decision problems and specific economic-ecological contexts.

Particularly in situations in which indeterminacy is important, contextual and local (lay) knowledge may contribute to the validity of models as has for example been demonstrated for a monitoring and modelling system for urban air pollution in an English town. The formalizations and idealizations incorporated into the model by (external) scientists did not account for specific local environmental conditions and the idiosyncratic behavior of social and biological actors. The authors of the study conclude that "to build robust and legitimate models, public bodies will need to devise methods of consultation and participation not only when the model is running, but also in setting out the objectives and parameters of the model in its earliest stages" (Yearly, 1999).

8. Conclusions

Dynamical systems are the reading frame for the scientific observation of ecological systems. The encoding of ecosystems in dynamical systems has been challenged in this article: (1) The sequence of selection leading to the encoding is relative to a specific domain of phenomena of interest, to the underlying theory and to a specific perspective, consisting of a set of distinctions and selections established by a certain discipline or "school". (2) Dynamical systems are defined by a closed set of variables, although in ecosystems there is an unlimited supply of things not accounted for in a given model (unmarked space). Simulation models have limited predictive capacity and it is impossible to validate them, so that they are deficient instruments for the reduction of uncertainty as to the behavior of ecological systems. However, models outline the space of behavioral possibilities and it is in this sense that they have anticipative value in decision processes, particularly as human impact on ecosystems presumably accelerates the production of novelty in ecosystems.

Normal science trains for abstraction, decontextualization and exo-perspectives and provides established methods (e.g. more and better data) for the reduction of uncertainty. In many environmental issues, however, uncertainty is of an epistemic nature and can only be partly remedied; coping with epistemic uncertainty in concrete contexts of application is not a particular strength of normal science. Where future system development cannot be predicted, let alone controlled (as contended by the notion of ecosystem engineering) the local, variable, temporal and spatial context gains importance; a multiplicity of endo-perspectives thus obtains priority over a universal exo-perspective (Nowotny, 1996). The concepts of Mode 2 and of post-normal science provide frameworks for such issues. However, Mode 2 and post-normal science, the precautionary principle and the contextualization of knowledge production challenge the established authority and the monopoly of science to define reality. Scientific perspectives, reading frames and descriptions of ecological and economic-ecological systems compete with other descriptions of the same system and the aptitude to define and frame problems interactively and transdisciplinarily are the test stand for a managerial science. The authority of science becomes tied to concrete practices, their results and impacts (Nowotny, 1999). These developments will presumably resonate in ecological modelling: On the one hand models may continue to make a contribution to ecological theory. On the other hand, modelling in the interstice between science and public policy may become embedded into the "deliberation frames analysis, analysis guides deliberation" framework. For this purpose models should become more transparent, framing of models and model choice and the evaluation of models should involve extended peer groups (stakeholders, local actors) and knowledge conveyed by models is to be configurated for concrete problem contexts. Modelling thus could contribute to the organization of knowledge, e.g. it could catalyze mutual learning processes and it could contribute to the integration of scientific and non-scientific knowledge and of exo- and endo-perspectives.

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> All streams flow into the sea, yet the sea is never full.
>
> Ecclesiastes

> Aber diese Schlechtmachung jenes Guten,
> das auch noch im vorhandenen Unvollkommenen steckt,
> können wir uns nicht leisten: endliche Wesen haben nicht so viele
> Eisen im Feuer, daß sie auf irgendeines verzichten könnten.
>
> Odo Marquard – Apologie des Zufälligen

G. LANDSCAPE FATE OF NITRATE FLUXES AND EMISSIONS IN CENTRAL EUROPE: A CRITICAL REVIEW OF CONCEPTS, DATA, AND MODELS FOR TRANSPORT AND RETENTION

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G. Landscape Fate of Nitrate Fluxes and Emissions in Central Europe: A critical review of concepts, data, and models for transport and retention

Abstract

Agroecosystems are leaky systems emitting nutrients like nitrate, which affect ecosystems on a range of scales. This paper examines the fate of nitrate on the landscape level focussing on how landscape components either facilitate or impede N translocation from the field to the stream (headwater). Acccording to their role in landscape metabolism, two categories of landscape components are distinguished, ecotones/retention compartments and conduits/corridors. Conduits such as macropores, preferential interflow-paths, drainage tiles and streams rapidly relocate nitrate to headwaters. Retention compartments like the capillary fringe/saturated zone and riparian vegetation eliminate N through denitrification. The differential role of compartments is illustrated with quantitative examples from the literature. On the landscape level retention potential for N is spatially variable and quantitatively limited, while its realisation is uncertain. Notwithstanding, the literature indicates that on a watershed basis the bulk of total N input is retained; thus the potential is discussed for the retention of nitrate on different scales, i.e., the field, landscape, regional and global scale. The transitory retention of excess nitrate in soil and subsoil solution, soil organic matter, groundwater and riparian vegetation may delay nitrate discharge to the aquatic system for decades, contributing to the low emission factors on basin scale. The adverse effects arising from denitrification are discussed, presenting data on the emission of nitrous oxide from the entirety of the different landscape compartments. It is concluded that reliance on landscape metabolism and self-purification postpones the problem of global N overload and partially transfers it to the atmosphere. An assessment scheme is presented which in the face of the unpredictability of ecosystem and landscape behaviour is risk oriented (instead of impact oriented). The scheme uses a budget approach, which accounts for the critical role of corridors and considers the scale and scope of N emissions. A conceptual framework for the remediation of N overload is presented which rests on the realisation of cycling principles and zero-emission approaches on all scales of agricultural production and which pleads for regional approaches that transcend sectoral boundaries and take account of overall regional N fluxes.

1. Introduction

Agricultural systems are ecosystems that are maintained in an immature state due to human intervention (Odum, 1969). Control is largely external (Odum, 1984), manifested by frequent external inputs of nutrients and energy, which are large compared to internal fluxes and cycling. As plants are regularly removed from the system, plant and decomposer activity are decoupled. Compared to natural ecosystems, agroecosystems are leaky systems with greater amounts of nutrients flowing in and out (Hendrix et al., 1992; Magdoff et al., 1997). The emitted substances are dispersed in the environment by transformation and transport processes. Transformation processes break up molecules, augment the number of “small molecules” (Addiscott, 1995) and thus increase entropy. Transport processes distribute substances along gradients of potential energy in the environment of agroecosystems.

Intensive N fertilisation and disrupted N cycles have brought about the emission of considerable amounts of N compounds. In terrestrial ecosystems N is mostly translocated as nitrate, which is subject to mass flow and leaching. Average nitrate leaching from terrestrial ecosystems in Central Europe is 15 kg $ha^{-1}yr^{-1}$: N leaching is 15.9 kg $ha^{-1}yr^{-1}$ in Germany (Werner, 1994), 15.0 kg $ha^{-1}yr^{-1}$ in the watershed of Lake of Constance, the second largest European lake (Prasuhn et al., 1996), and 14.7 kg $ha^{-1}yr^{-1}$ in the canton Bern in Switzerland (Prasuhn and Braun, 1995).

The scope of N impacts ranges from adverse effects on (ground-)water quality over acidification and eutrophication of aquatic ecosystems to loss of biological diversity, and to impacts on atmosphere and climate, e.g., nitrous oxide as greenhouse gas (Lehn et al.; 1995, Vitousek et al., 1997a). Ecosystems on a variety of scales are affected by N emissions. On the local scale, groundwater quality and headwaters are affected. On the regional scale, rivers and lakes receive large N loads, roughly half of it deriving from agriculture; e.g., in the European Union rivers receive 55% (Isermann and Isermann, 1997) and in Germany 44 % (Werner, 1994) of total N input from agriculture. Agricultural activities account for 64% of N input into the Lake of Constance and to natural background concentration for only 36% (Prasuhn *et al.*, 1996). Rivers discharging into seas are a major conveyor of N. With respect to N, the North Sea drainages are among the most disturbed regions: Average net anthropogenic N input into watersheds is 3900 kg $km^{-2}yr^{-1}$, 83 % of which derive from fertilisers. The resultant discharge to the sea is 1450 kg N $km^{-2}yr^{-1}$ on average (Howarth et al., 1996). This paper therefore focuses on the fate of agricultural N in Central Europe.

2. Assessing N fluxes in agroecosystems

A variety of approaches has been developed to assess the N fluxes arising from agricultural production and to evaluate potential impacts on the environment.

On the field scale, the risk of N loss is assessed with index models, budget approaches and simulation models. Index models characterise risks only qualitatively. Examples are DRASTIC (Aller et al., 1987) and KUL (Eckert and Breitschuh, 1994; Kerschberger and Eckert, 1994). Index methods such as DRASTIC correlate only weakly with measured nitrate inputs into the groundwater (Canter, 1997), hence they are only suitable for the tentative screening of problem areas. Budget approaches indicate site specific risk of N loss and potential disequilibria (Bach, 1987; PARCOM, 1994; Wendland, 1994). Simulation models for the N cycle represent processes of the N cycle at point and field scale (de Willigen, 1991; de Willigen and Neetson, 1985; Groot et al., 1991). They have been applied to study the effect of certain agricultural measures on emissions on field scale, e.g., (Dijkstra and Hack, 1995; Line et al., 1993; Rode et al., 1995). However, the simulation of N dynamics and the assessment of output potentials neither address the path nor the fate of nitrate emissions.

Recently, attempts are made to adapt life cycle assessment procedures to agricultural production systems (Vito, 1998). Life cycle approaches assess the impact of agricultural production systems on the environment in terms of effect potentials; they disregard the spatial dimension and setting.

On a catchment scale, agricultural non-point-source (Ag-NPS) models are employed. They usually are built on field-scale models of losses that are aggregated at the catchment scale. Ag-NPS models in conjunction with GIS applications have been used to investigate the relation between land use (i.e., land cover pattern and land use proximity to stream channels) and N chemistry (Hunsaker and Levine, 1995; Tufford et al., 1998) and to study the impact of best management practices on water quality (Hession et al., 1989; Prato and Shi, 1990; Tim and Jolly, 1994). Models are compared by Novotny (1986), Line (1993), while Loague et al. (1998) draw attention to the uncertainties intrinsic to this approach. Key limitations of the Ag-NPS models are twofold (Merot and Durand, 1997). Firstly, they are distributed models resting on the assumption that parameters for each individual cell are perfectly known and that the catchment response is the aggregation of the functioning of the cells. Secondly, the classical Ag-NPS models such as ANSWERS or AGNPS do not explicitly take account of retention zones like hedges or riparian vegetation, overlooking processes which are essential for the functioning of buffer zones.

The mentioned approaches only crudely address the role of the landscape into which agricultural sites and affected ecosystems are embedded and in which transport and retention of matter take place. Leached nitrate passes a number of compartments and landscape elements prior to discharge to the aquatic system. Having left the root zone, nitrate passes the vadose zone (subsoil) and a capillary fringe, eventually reaching an aquifer. Often distinct aquifer storeys coexist, in particular an unconfined shallow aquifer may be underlain by (semi-)confined, deeper aquifers. Lateral transport of nitrate takes place in interflow, drainage tiles and aquifers. A riparian zone may be crossed prior to discharge into a stream. The hydrological setting and the resultant hydrological routing can be rather complex, steering contact times and time lags between in- and output and retention. Retention of nitrate is either due to plant uptake or to denitrification. While the first represents temporary storage in the system, the latter leads to the elimination of N from the system. The steering factors and conditions of denitrification in laboratory and field have been discussed elsewhere (Ferguson, 1994, Groffman et al., 1987). The different compartments function as "landscape organs" (Rapport et al., 1998) contributing to a specific landscape metabolism. With the metabolism metaphor the idea of the "self-purification" of both terrestrial and aquatic systems is associated. Yet where in the landscape retention actually takes place and whether retention potentials can be sustained in the long run, is not clear.

In the following landscape metabolism and its potential elements are investigated. Based on the concepts of hierarchy theory, sustainability and landscape diversity (Barrett, 1992), a conceptual framework is developed for the distinction of interfaces and corridors. Interfaces or ecotones are landscape organs attenuating matter fluxes and their impact on aquatic media; corridors lead to the rapid translocation of matter, increasing environmental risks. A review is provided of the retention or transport potential of the different compartments along the way from the field to headwaters, which dominate water quality downstream and which consequently should have priority in water protection (Haycock et al., 1993). The retention potential of landscapes is critically discussed and the wide scale and scope of nitrate losses is highlighted. Finally, a risk assessment scheme and concepts for remediation are sketched, taking account of the unpredictability of ecosystem behavior and of the importance of balanced budgets and closed nutrient cycles. It is concluded that sustainable agricultural management should avoid end-of-the-pipe solutions (relying e.g. on the retentive potential of riparian vegetation), but employ scalar system approaches, in which natural cycling principles should be the benchmark for best management.

3. Conceptualisation of nitrate transport and retention

Landscapes are heterogeneous "patch-works", in which spatial pattern and processes interact (Turner, 1989) to produce domains in which either retention or transport of matter dominates. The ensuing landscape elements operate as biogeochemical processors of matter, governing matter fluxes and budgets on the landscape level (Frede and Bach, 1995). Ecosystem theory conceives landscape elements as components of a nested, inclusive hierarchy with holons as the basic units (Ahl and Allen, 1996, Allen and Hoekstra, 1992). Transfers and processes inside a holon are more intensive than the connexions between different holons, while process rates exhibit steep gradients at the margins of holons (Müller, 1992). Holons are delimited by boundaries which act as differentially-permeable membranes facilitating some ecological flows but impeding others (Wiens et al., 1985).

3.1. Retention elements

Boundaries are locations where the rates of ecological transfers tend to change abruptly; they increase landscape resistance (Forman, 1995), and they are important control points for material flux (Naiman et al., 1988). Spatially they are expressed as transitional zones or ecotones (Hansen et al., 1988), particularly at aquatic-terrestrial interfaces (Naiman, 1990). Ecotone width depends on the type of flux under consideration, with physicochemical flows creating the widest ecotones (Gilbert et al., 1990). Retention in transition zones is due to storage in pools with long turn-over times, e.g., nutrient stocks in vegetation (Johnston, 1991) or the passive soil carbon pool with turnover times of up to 1000 years (Parton et al., 1988);

retention also includes elimination and transfer to the atmosphere (denitrification). Retention is largely determined by retention time and area of contact. Accordingly, water retention time is the most critical factor for N removal in wetlands (Jansson et al., 1994a). From a landscape health perspective interfaces are critical landscape organs (Rapport *et al*., 1998), regulating the flow of materials across landscapes and acting as sinks in landscape transport (Tim and Jolly, 1994).

3.2. Corridors

Corridors are conduits connecting holons and elements of larger scales (Allen and Hoekstra, 1992). Corridors are expressed structurally as preferential flow-paths on different spatial scales. They usually are part of a hierarchical pattern of flow-paths. For example in funnel flow, water is gradually congregated into preferential flow paths and its movement can be conceptualized as a network of tributaries merging into rivers (Ju and Kung, 1997). Macropore networks have been found to be continuous laterally (interflow) and vertically (Mosley, 1982). Other examples for the hierarchical pattern of corridors are linear forms of erosion (Helming and Frielinghaus, 1998), and the network of streams and rivers (Petts, 1994). Typical corridors are illustrated schematically in Figure G.1.

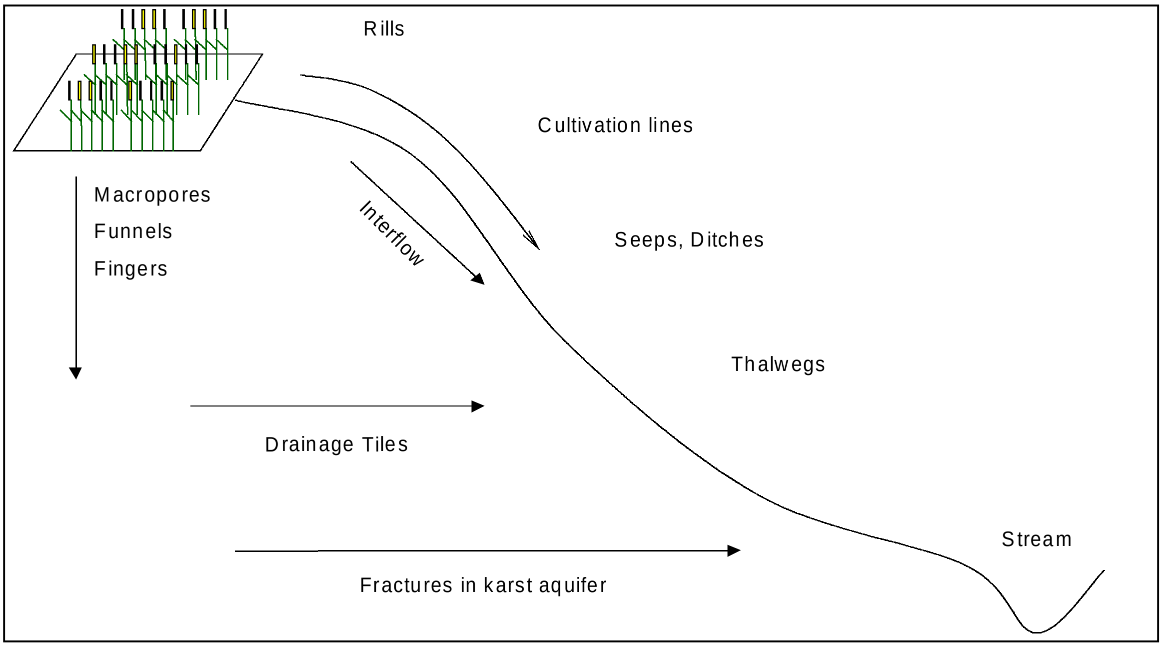

Figure G.1. Corridors in an agricultural landscape. Corridors are doorways of the agricultural system, through which substances bypass on-site and off-site retention zones and are conveyed directly and quickly to the aquatic system. Note the hierarchy of surface corridors, ranging from rills to streams.

In corridors matter translocation is rapid, so that residence time is shortened, retention zones are bypassed and spatial distances are bridged. Substances are “flushed through” corridors and internal processing of matter entailing transformation, cycling and retention is restricted (Fig. G.2). Contact and interaction with corridor boundaries is limited. For example in soils there is hardly any lateral interaction between corridor and soil matrix in macropore or funnel flow (Ju and Kung, 1997). In the fluvial system of headwater catchments, the physical and chemical processes are dominated by longitudinal processes as well (Petts, 1994).

While holons, boundaries/interfaces and corridors are conceived theoretically, spatially explicit compartments can be classified as retention, intermediary and conduit compartments (Fig. G.2), based on overall partitioning between transport and retention of matter .

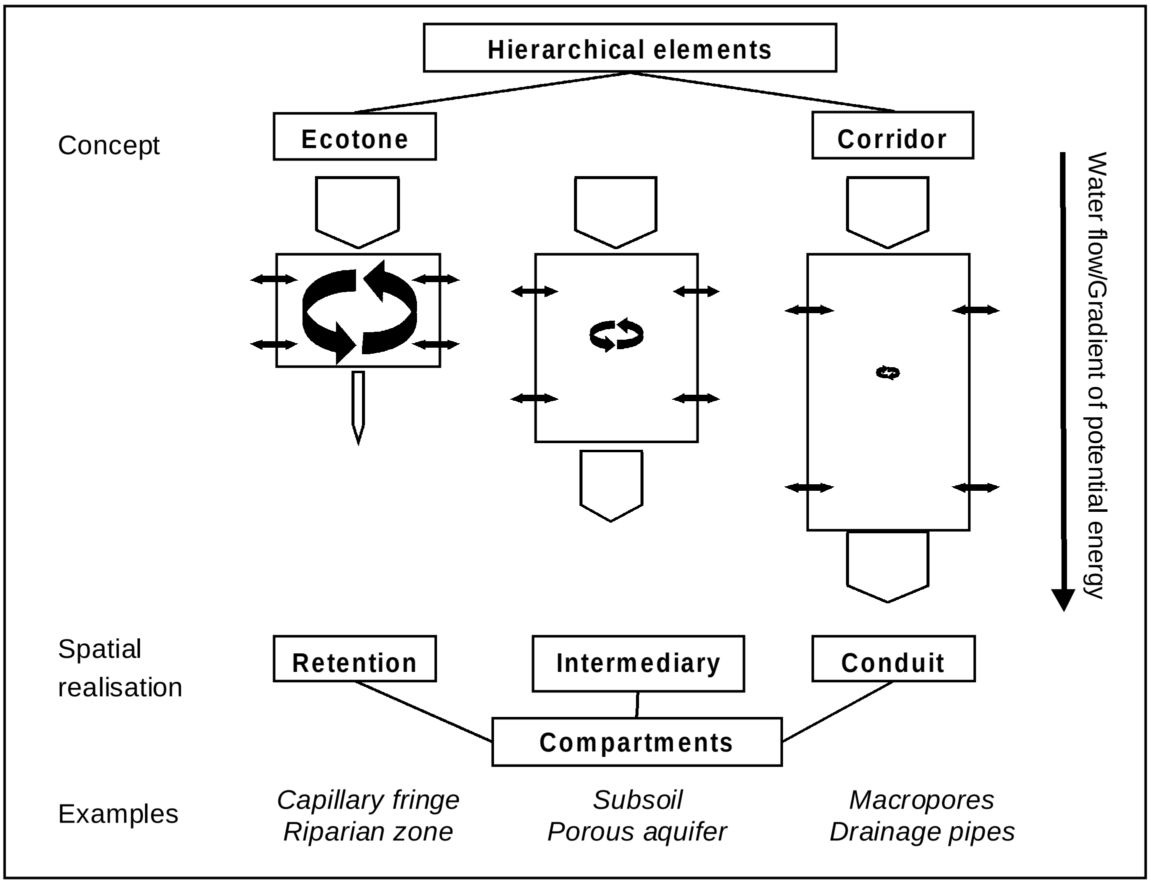

Figure G.2. Classification of landscape elements and compartments. Ecotones and corridors are conceived conceptually. Compartments are explicit sections of space, which are distinguished according to overall matter processing rate. Water flow follows gradients of potential energy. Towards the lateral boundaries of the compartments process rates decline. Internal cycling (indicated by circular arrows) and residence time (indicated by reciprocal of length) varies considerably. In conduits residence times are particularly low. The terms corridor/conduit and ecotone/retention compartment will be used interchangeably in the text.

3.3. Focus on nitrate leaching to headwaters

Agricultural contaminants differ with respect to their affinity to determined transport mechanisms. Based upon their soil-solution-partitioning coefficient they can be assigned preferential transport mechanisms (Fig. G.3).

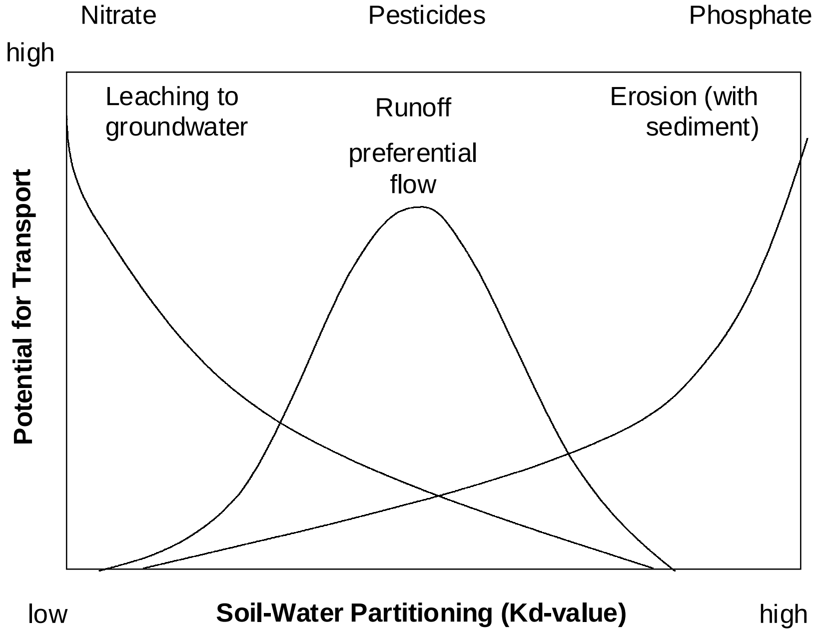

Figure G.3. Affinity of agricultural contaminants to different mechanisms of transport as a function of their soil-water partitioning coefficient. For nitrate, leaching is the dominant transport process, while superficial transport in run-off water and with eroding soil is of minor importance (adapted from Logan, 1993).

Nitrate as a highly water-soluble substance is prone to leaching with mass flow. The Lake of Constance study illustrates the dominance of leaching as transport mechanism. Leaching accounted for 79 % of NPS, while run-off was a minor source (3 %) and erosion was relevant in the Alpine parts of the watershed only (Prasuhn *et al.*, 1996). Under certain conditions, runoff plays a more prominent role, e.g. in some major estuaries, such as Delaware Bay and Chesapeake Bay, NPS runoff from terrestrial ecosystems accounted for half or more of total N inputs (Cronan et al., 1999). Yet as in Central Europe up to 80 % of river water stems from groundwater (Hamm, 1991) and owing to the general relevance of leaching this paper focuses on subsurface processes. A characteristic sequence of compartments nitrate traverses on its way from the field to the stream is shown in Figure G.4.

From a water quality perspective, protection of headwaters should have priority (Haycock *et al.*, 1993), as on a catchment scale 60% to 70% of the water in large rivers enters the system via first to third order streams (Vought et al., 1994). According to Kirkby (1978) even 90% of the flow of rivers comes from headwaters, defined as first- and second-order streams. Thus low-order streams contribute the highest percentage to the loading of rivers with nutrients and pesticides (Bach et al., 1997). The approach of this study, therefore stresses the loading of headwaters.

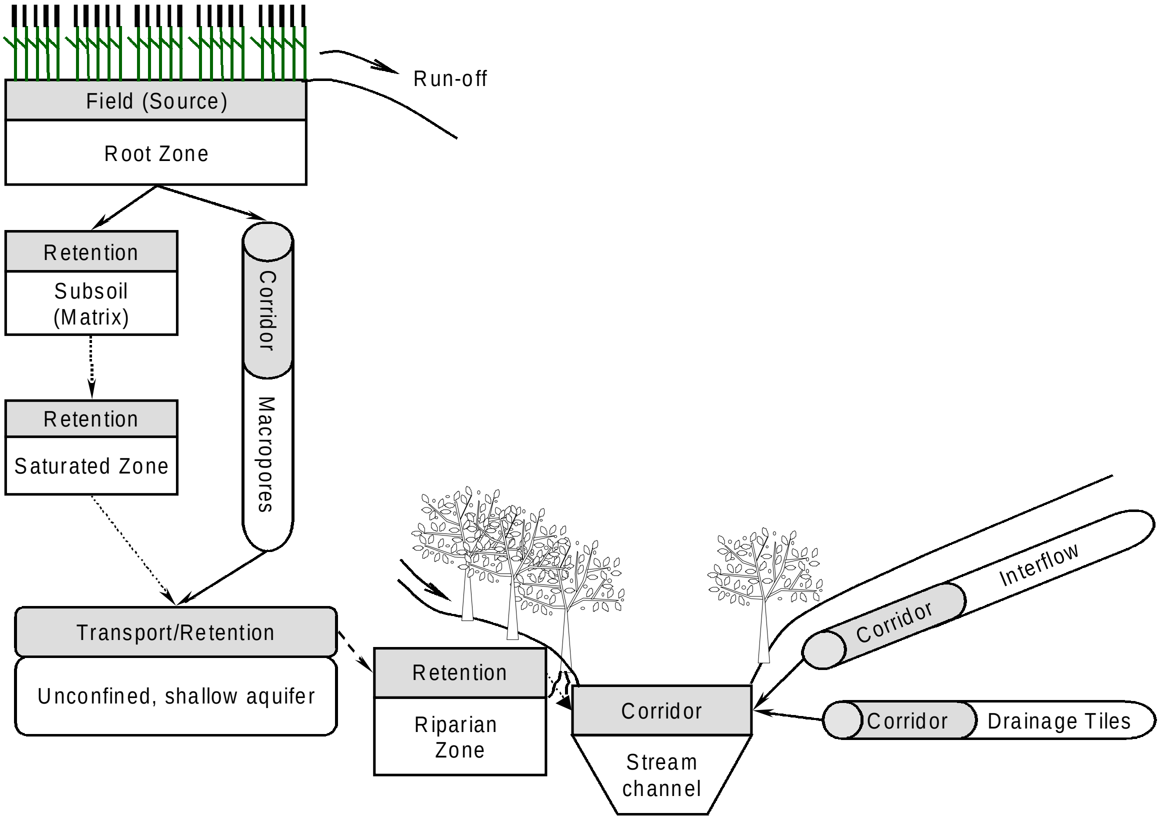

Figure G.4. Schematic of corridors and retention compartments. The sequence of compartments depends upon the specific hydrological setting and is spatio-temporally variable.

4. Retention in landscape compartments

The different compartments on the way from the field to the headwater are highlighted (Fig. G.4) and their role in landscape N metabolism is illustrated with experimental data from a variety of studies in the following section.

4.1. Soil and subsoil

Organic carbon is the key limiting factor for denitrification in subsoils, so that movement of carbon from the soil surface is necessary to support denitrification (Rice and Rogers, 1993). Anaerobic conditions are another precondition. Soil morphology, particularly the existence of stratified layers within the soil profile, impeding water and solute movement may contribute to the creation of conditions favorable for denitrification (Zakosek and Zepp, 1993). Depending upon soil type and agricultural land use denitrification losses ranged from 1 kg N $ha^{-1}yr^{-1}$ to 223 N kg $ha^{-1}yr^{-1}$ in a number of field experiments (Wendland, 1992).

However, denitrification in subsoil and intermediate vadose zone may be insignificant under certain conditions (Rice and Rogers, 1993; Zakosek and Zepp, 1993): For example unstratified coarse textured soils either lack organic carbon or anaerobic conditions. Fine textured soils may lack organic carbon; e.g., in some loess subsoils denitrification has been shown to be insignificant due to the lack of organic C and thus played no role in the reduction of nitrate transfer into the groundwater (Heyder, 1993). Under normal field conditions subsoil denitrification potential and its rate of recovery tend to be low (Zakosek and Zepp, 1993). Residence time of leachate in soil and underlying substrates varies from days (karst) to decades (fine-textured, thick substrates without fissures), thus N passage to aquifers may be retarded considerably (Hölting et al., 1995).

4.2. Groundwater and aquifers

Groundwater and aquifers diverge with respect to landscape position, chemical characteristics, permeability and vulnerability to agricultural inputs, (Hölting *et al.*, 1995). Three aquifer types can be distinguished (Davis and DeWiest, 1991; Hölting, 1980): Unconsolidated, porous aquifers (gravel, sand), consolidated aquifers (cracks in solid rock) and karst aquifers (fractures). Retention takes place in transition zones (Gilbert *et al.*, 1990), while fissures and fractures serve as conduits. Depending upon permeability and biological/chemical characteristics, aquifers as a whole can act as conduits (e.g., karst aquifers with wide fissures) or as retention compartments (e.g., aquifers with low permeability and high denitrification potentials). Groundwater transport usually is slow compared to superficial water flow and can retard discharge of nitrate to streams for years or decades (see below).

4.2.1. Denitrification studies

Substantial denitrification has been observed in a variety aquifers (Hiscock et al., 1991; Korom, 1992; Lowrance and Pionke, 1989; Mariotti, 1994; Rice and Rogers, 1993; Spalding and Parrot, 1994), while in other aquifers little or no denitrification activity was observed (Hiscock *et al.*, 1991; Lowrance, 1992; Lowrance and Pionke, 1989; Mariotti, 1994; Rice and Rogers, 1993). Actual and potential denitrification depend on biological and chemical characteristics and on hydrology (Mariotti, 1994). The key limiting factor of heterotrophic denitrification is organic carbon availability, while populations of denitrifiers exist in both shallow and deep aquifer systems (Hiscock *et al.*, 1991; Mariotti, 1994). Autotrophic denitrification, requiring an inorganic source for oxidation, e.g., pyrite, is uncommon in groundwater (Hiscock *et al.*, 1991).

4.2.2. Shallow unconfined aquifers

Denitrification may be an important mechanism for reducing nitrate within selected landscape positions, especially in near proximity to the water table (Steinheimer et al., 1998), i.e. in the transition zone between unsaturated and saturated zones. Correspondingly, it appears to be of greatest significance in shallow unconfined aquifers (Rice and Rogers, 1993), where denitrification is considered an important mechanism attenuating nitrate concentration (Lowrance and Pionke, 1989; Montgomery et al., 1997). Within the lower Rhine region in Germany nitrate reductions for three shallow ground water catchments were 16 %, 63 % and 70 % of the nitrate reaching the aquifer (Obermann, 1982). In a superficial pleistocene aquifer, dissolved carbon leached into groundwater yielded maximum potential denitrification of 65 mg l^{-1} nitrate (Leuchs, 1988).

4.2.3. Hydrological setting

The hydrological setting is crucial for denitrification particularly in shallow aquifers. In Central Europe three typical constellations were found, showing the wide range of denitrifcation potential and stressing the relevance of organic carbon (Obermann, 1991). Firstly, consolidated aquifers with little soil cover and high permeability in combination to high nitrate inputs entailed correspondingly high nitrate output; discharge of nitrate was only delayed. Secondly, unconsolidated aquifers with low amounts of organic carbon in combination with limited nitrate input led to partial elimination of nitrate. Thirdly, unconsolidated aquifers with high amounts of organic carbon caused almost complete elimination of nitrate.

4.3. Terrestrial-aquatic interfaces and riparian zones

There seems to be general agreement that the land-water interface regulates water quality in agricultural watersheds (Dillaha et al., 1989), making riparian buffers the most important factor controlling entry of non-point source nitrate in surface water (Gilliam et al., 1997). Thus buffer zones are attributed an enormous potential for the control of water-based pollution (Haycock et al., 1997). Riparian zones may improve water quality due to sedimentation, plant uptake, retention in soil and microbial processes (Correll, 1997; Johnston, 1991; Vought *et al.*, 1994). Particularly denitrification, which ultimately exports N from the system, is very common in wetland ecotones (Gilbert *et al.*, 1990).

4.3.1. Field and Laboratory studies

Denitrification losses from riparian forests in Georgia and Maryland ranged from 61 to 89 % of N inputs, while retention ranged from 39 kg ha^{-1} (32 kg ha^{-1} due to denitrification and 7 kg ha^{-1} due to net retention within the system) to 74 kg ha^{-1} (Johnston, 1991). In riparian zones of the river Garonne in France, denitrification was so intensive that approximately 30 m of groundwater flow under a woodlot were enough to remove the entire nitrate (Pinay et al., 1990). A riparian zone located below and adjacent to a field-sized watershed planted with soybeans eliminated up to 93 % of groundwater nitrate (Line, 1993). In a large number of studies riparian nitrate removal exceeded 90 % (Hill, 1996) and removals of 90 % seem to be common. However, at least some wetlands seem to retain little if any N. In a study of 5 wetlands in Ontario, Devito (1990) reported net retention ranged from -12 % to + 4 %. The overall range of N retention in wetlands is around - 30 % to + 100 % (Johnston, 1991), i.e. depending upon wetland, net release of nitrate and complete retention of nitrate are possible.

Denitrification potentials have been studied in field and laboratory. Mesocosm experiments yielded denitrification potentials of 29 kg $ha^{-1}yr^{-1}$ and 171 kg $ha^{-1}yr^{-1}$ for similar sites (Addy et al., 1999), demonstrating the influence of land use legacy. Under incubated laboratory conditions an average of 76 kg $ha^{-1}yr^{-1}$ was assessed, while soil amended in situ with N reached values of 160 kg $ha^{-1}yr^{-1}$ up to 1340 kg $ha^{-1}yr^{-1}$. However, under unamended in situ conditions, average was only 2 kg $ha^{-1}yr^{-1}$ (Johnston, 1991) demonstrating that actual denitrification in riparian zones is easily overestimated.

4.3.2. Hydrological setting

A major factor for the realization of retention potentials and the effectiveness of buffer zones is hydrological setting (Fig. G.5) (Addiscott, 1997; Correll, 1997; Gilliam *et al.*, 1997; Haycock *et al.*, 1997). It determines residence time, which is the single most important variable for water quality improvement (Fennessy and Cronk, 1997).

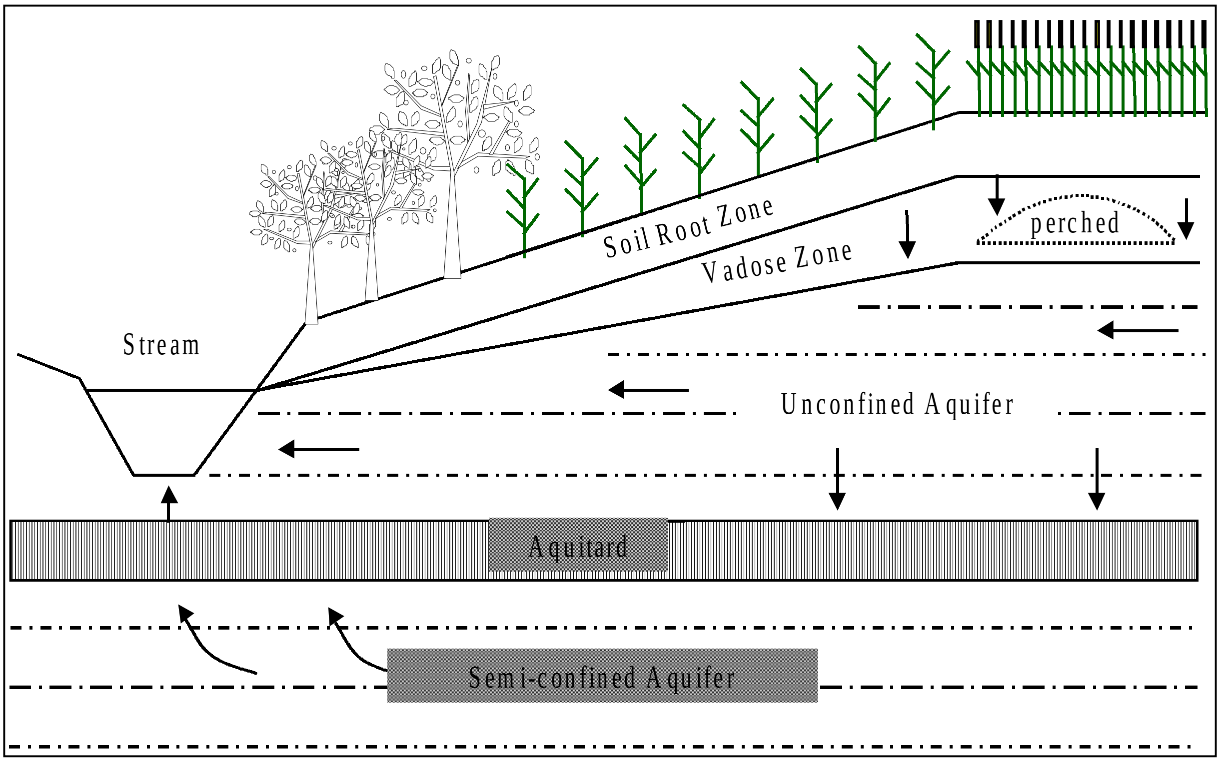

Figure G.5. Schematic of vadose zone, aquifers and flow directions in a typical riparian zone in a humid climate (adapted from Lowrance and Pionke (1989). The hydrological setting determines, whether leached nitrate is subject to riparian retention or bypasses it. Drainage tiles and interflow are not depicted.

For example in a controlled situation at least 10 days of water retention was needed to remove N (Hillbricht-Ilkowska, 1995). Riparian forests of different hydrological positions thus vary in nutrient retention (Risser, 1990) and buffer zones work well only under determined hydrological conditions (Hill, 1996). Effective removal is restrained to riparian zones with permeable surface soils and sediments that are underlain at a depth of 1 to 4 m by an impermeable layer that produces shallow subsurface flow of groundwater across the riparian area. Riparian zones connected to large aquifers may be less effective as interaction with vegetation and soils is restricted. To improve the buffer function, water regime is to be managed aiming at increased residence time within the system (Haycock *et al.*, 1993).

4.3.3. Optimum width

There is no consensus regarding width of riparian zones, except that minimum width is 10 m (Haycock *et al*., 1993), while less than 5-10 m provide little protection of aquatic resources (Castelle et al., 1994). Nitrate reductions of 100 % seem to be approached by a width between 10 m and 20 m (Vought *et al*., 1994) or 20 m and 30 m (Fennessy and Cronk, 1997). Given the complexity of the riparian setting, a useful retort to the question of width is "how wide do you want it?" (Haycock *et al*., 1997).

4.3.4. Sustainability of retention

Seasonal and long-term sustainability of riparian buffers is controversial as well (Addiscott, 1997). The seasonal sustainability of retention in riparian zones may be maintained in summer by vegetation uptake and during the dormant season by denitrification, as denitrification takes place as soon as the soil temperature exceeds 4° C (Haycock *et al*., 1993). Other authors, however, stress the seasonal variability of retention, the role of extreme (e.g., storm) events and the decoupling of peak emissions and maximum of retention activity (Addiscott, 1997; Hill, 1996). Long-term sustainability may be affected by declining availability of organic carbon for denitrification and decreasing uptake by old vegetation (Haycock *et al*., 1993). Moreover there may be an upper limit for the retention of agricultural loads. In wetlands only amounts below 200 kg N $ha^{-1}yr^{-1}$ could be removed satisfactorily (> 80%), while the long-term application of higher loads resulted in removal of less than 40 % (Hillbricht-Ilkowska, 1995).

4.4. Aquatic-aquatic interfaces: Hyporheic zone and sediments

The hyporheic zone is an active ecotone between the surface stream and groundwater. Connections are bidirectional (Bencala, 1993); exchange of water, nutrients, and organic matter occur in response to variations in discharge and porosity (Boulton et al., 1998). Particularly sediments act as sinks for nitrate that discharges to streams and rivers (Gilbert *et al*., 1990; Pfenning and McMahon, 1996). Laboratory incubation suggests that nitrate is rapidly depleted below the sediment-water interface (Hill, 1997). In the sediments of the river Dorn in Oxfordshire denitrification accounted for 15 % of nitrate entering under baseflow conditions (Fennessy and Cronk, 1997). Estimates of the magnitude of N removal during the summer season, when streams are frequently at base flow range from <10 % to 76 % in a number of studies (Hill, 1997). However, potential denitrification tends to be limited by organic carbon and low temperatures; e.g., potential denitrification measured at 4° C was 77 % lower than at 22°C in lab experiments on Australian river sediments, supposedly contributing to high nitrate concentration in the river during winter (Pfenning and McMahon, 1996). In any case, overall in-stream denitrification will be much less than in adjacent riparian wetlands (Fennessy and Cronk, 1997).

Transport in corridors

5.1. Preferential flow

Preferential flow takes place in macropores, fingers and funnels (Ju and Kung, 1997; Jury and Flühler, 1992; Stagnitti et al., 1995). Preferential flow has been observed under a variety of conditions, from sandy to clayey soils. Biopores, e.g., well connected root channels of wheat (Triticum spp.), alfalfa (Medicago sativa L.) and corn (Zea mays L.) may induce preferential flow (Li and Ghodrati, 1994). Preferential flow is not predictable in advance from field analysis (Bouma, 1992; Jury and Flühler, 1992). Rapid movement of nitrate along macropores has been observed (Bouma, 1992). For example in a heavy clay soil rapid nitrate leaching via preferential flow through mesopores and macropores was observed leading to average nitrate concentrations of 70 mg l^{-1} and maximum concentrations of 136 mg l^{-1} in drain discharge (Bronswijk et al., 1995). While gaps in the N balance often are attributed to denitrification, bypass flow may sometimes be a more important process (Dekker and Bouma, 1984).

5.2. Interflow

Interflow has been observed as an important mechanism for the rapid transport of nitrate towards streams, particularly under stormflow and snowmelt conditions (Göttlicher-Göbel, 1987; Mosley, 1982; Peter, 1987). In forested watersheds average subsurface flow velocities were as high as 0.3 cm s^{-1}, due to flow along macropores and along layers at which permeability changed abruptly. (Mosley, 1982). In small watersheds, nitrate peaked in streams due to interflow after stormflow (Peter, 1987). At the beginning of the winter leaching period, nitrate concentrations in the interflow of a loess site peaked, while denitrification was low (Steininger et al., 1997). Preferential flowpaths may circumvent retention zones, as e.g., has been demonstrated for riparian zones in Britanny (Bidois, 1999).

5.3. Drainage tiles

Drainage tiles inducing artificial interflow are particularly rapid conduits. Artificial drainage speeds the movement of water and contaminants such as nitrate, reducing the opportunity for denitrification to take place (Fennessy and Cronk, 1997). In a number of studies, nitrate concentrations have been obseserved to range from 2 to 20 mg NO_3 l^{-1} under mineral soils (Hamm, 1991). Average annual nitrate N loss to subsurface drains has been shown to range from 14 to 105 kg a^{-1}, with most of the loss occurring in the winter season (Kladikov et al., 1999). Drainage tiles can contribute significantly to water pollution. For example, around 60 % of nitrate-N in surface waters in Illinois entered through drainage tiles (Kohl et al., 1971). Flood events can lead to large export of N in tiles; accordingly, a few days of high-flow events led to most of the annual nitrate loss from a tile-drained field (David et al., 1997). In many areas, subsurface drains discharge into surface ditches or streams (Kladikov *et al.*, 1999). Thus large amounts of N may reach streams through drainage tiles emptying directly into the channel without contact with the riparian soil (Vought *et al.*, 1994).

5.4. Surface flow

Superficial preferential flow minimizes contact with the soil matrix and conveys nitrate rapidly and directly into the aquatic system, overrunning retention compartments such as riparian vegetation (Bach *et al.*; 1997, Bach et al., 1994). Preferential flow paths are part of a hierarchical network (Fig. G.1), consisting of intermittent elements such as rills, cultivation lines and tracks, thalwegs and ephemeral gullies (Helming and Frielinghaus, 1998) and of more permanent streamlets. Drainage lines and streamlets change position and features constantly and despite their importance as conduits removing substances quickly from the field they are overlooked easily. For example a typical drainage line or streamlet in Central Germany had a depth of only 3 cm and an average width of 63 cm, giving rise to an overall streamlet surface of 630 m^2 km^{-2} (Bach et al., 1996). Once substances enter preferential flowpaths, retention is minimized.

5.5. Streams

Streams are "bodies of water moving to a position of lower energy" (Bren, 1993); they are highly dynamic in time and space and are difficult to distinguish from lesser forms like drainage lines or seeps. Uptake and denitrification in streams is limited; the bulk of denitrification probably takes place in aquatic ecotones (sediment) and not in the stream channel itself. In a small Scandinavian reach of 7 km length retention was less than 3 % of total N transport in the stream (Jansson et al., 1994b). In a Canadian basin denitrification was less than 6 % of the annual export of total N from the basin, while macrophyte uptake accounted for 15 % (Hill, 1988). In two rivers in the USA, 7 % and 35 % of the N load received from external sources was denitrified (Fennessy and Cronk, 1997). Annual mass balances indicate that nitrate-N removal ranges from 1 -5 % in many streams, although values of 20 % where also estimated (Hill, 1997).

5. Retention of nitrate on different spatial and temporal scales

In a scalar approach to N fluxes and cycles, four levels can be distinguished (Fig. G.6): Firstly, the field and adjacent ecosystems. Secondly, a local level which is restricted to low-order streams and ponds and their watershed. Thirdly, a regional level, which encompasses rivers and lakes like the Rhine, the Danube or the Lake of Constance and their respective basin. Fourthly, a global level, which includes seas like the North, the Baltic and the Black Sea and the atmosphere as a sink for gaseous emissions.

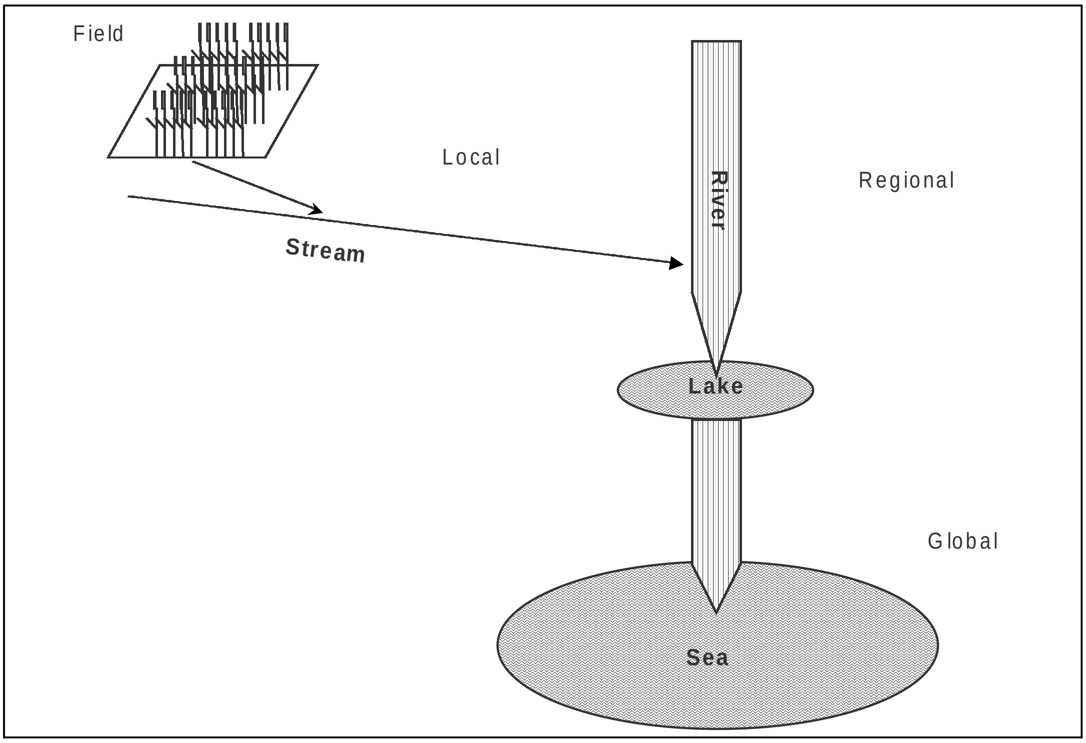

Figure G.6. Scalar approach to water quality, in which four levels are distinguished: The field as the source system including adjacent terrestrial ecosystems, the local level with streams of low order and occasional ponds, the regional level with rivers and lakes and the global level with seas and the atmosphere.

6.1. Local scale and limitations to retention

On local scale, the capacity of landscape metabolism to retain or eliminate excess N depends upon the pattern and interaction of retention compartments and corridors. Retention and elimination of leached nitrate has been demonstrated for many compartments, but retention is variable, limited and unpredictable as is illustrated for aquifers and for riparian zones:

In groundwater the availability of oxidizable material and residence time limit denitrification Owing to these constraints in groundwater only a potential for removing up to 3 mg N l^{-1} can be assumed under normal circumstances (Hiscock *et al.*, 1991). Moreover, organic carbon may be depleted at a higher (unsustainable) rate than it is replenished: A number of studies indicates that currently both autotrophic and heterotrophic denitrification potentials are being depleted, with the risk of a nitrate "breakthrough" in the future (Borchers, 1993; Böttcher et al.; 1990a, Böttcher et al., 1990b; Obermann, 1991).

Riparian zones have been attributed a particular significance in water quality protection. However heterogeneity in terms of soils, biogeochemistry and water pathways (Merot and Durand, 1997) complicates the understanding of the mechanisms controlling riparian zone functioning. Accordingly, results concerning actual retention capacities are controversial (Steinmann, 1991) and both high and little or no denitrification have been observed in a number of studies (Groffman and Gold, 1998). Some riparian zones may even release N

(Steinheimer *et al.*, 1998). Variability in nitrate removal among sites and within different domains is high (Hill, 1996). Ground water nitrate removal rates may differ even among sites with similar texture, drainage class and morphology (Addy *et al.*, 1999). Caution is required against ascribing specific ground water removal rates to different riparian zones and vegetation. Seasonal and long-term sustainability of the system are also questionable. The restoration of buffer zones with an optimum width > 10 m is difficult to accomplish in densely cultivated agricultural landscapes like in Central Europe. Nevertheless some authors assume that approximately 50 % of the N that is leached is denitrified in riparian forests and groundwater (Groffman and Gold, 1998). Others however claim that "scientists have frequently oversold the ability of wetlands to retain sediments and nutrients" (Johnston, 1991) and that riparian zones can only be a partial solution of a more comprehensive remediation policy (Bidois, 1999). Moreover, the impact of nutrients on wetlands as ecosystems of their own right requires more consideration. In summary, the potential for retention of nitrate on the way from the field to the stream is spatially and temporally restricted and its realization is uncertain.

Corridors connect spatial elements and scales and thus transcend space. Emissions to corridors generally increase environmental risks: Nitrate is rapidly lost from the system of origin circumventing retention potentials and decoupling the N cycle spatially and temporally; eventually emissions and their impact are aggregated on higher scales, where they elude human control. While leading to the rapid translocation of substances, flow in corridors is highly unpredictable.

6.2. Overstrained landscape retention

Anthropogenic N input into terrestrial ecosystems overstrains the capacity of landscapes to retain N. The transfer of N from the atmosphere into the land-based biological N cycle has at least doubled since preindustrial times (Vitousek *et al.*, 1997a), i.e. human activity adds at least as much N to terrestrial ecosystems as do all natural sources combined (Vitousek et al., 1997b). Large parts of this (global) overload are discharged to the aquatic system. Movements of total dissolved N into most of the temperate-zone rivers discharging into the North Atlantic Ocean may have increased by 2 to 20-fold since preindustrial times, while for rivers in the North Sea region, the N increase may have been 6 to 20-fold (Howarth *et al.*, 1996). Nitrogen fertilizers eventually end up in estuaries and continental shelves (Kroeze and Seitzinger, 1998).

6.3. Regional scale and retention on basin scale

Although N load to the sea is high, the percentage of total N input into watersheds which is actually discharged is remarkable small: Watersheds in Central and Northern Europe, but also elsewhere discharge only 20 % of overall N input to the sea and retain up to 80 % (Caraco and Cole, 1999; Howarth *et al.*, 1996). One reason may be denitrification and sedimentation on the regional scale: denitrification in rivers and particularly in riverine ecotones, like wetlands and sediments (Vitousek *et al.*, 1997a) may contribute to N elimination. In-river processes account for losses of around 10 to 20 % of total N inputs (Howarth *et al.*, 1996), while values of 50 % can be attained by heavily polluted rivers like the Scheldt (Billen et al., 1985). Retention in lakes and impoundments ranges from 20 to 80 % (Howarth *et al.*, 1996). Productive lakes may remove 50 % of total N input, with denitrification accounting for one third, while the rest is trapped in sediments (Jansson *et al.*, 1994a). Nitrogen budgets on basin level indicate that e.g., in the Rhine basin 85 10^6 kg of N are denitrified (the equivalent of 33 % of total input), while in the Elbe 75 10^6 kg (40 % of input) are denitrified (Werner, 1994).

6.4. Temporal scales and memory effects

On the local scale, retention may be due to denitrification, but temporary storage in soil (soil organic matter), vegetation and groundwater contribute substantially to the transitory attenuation of nitrate overload. Long residence times in soil and groundwater and the incorporation of N into vegetation and soil organic matter are followed by subsequent, slow release. Apparently there is a considerable memory effect in ecosystems concerning past nutrient input. In agroecosystems, fertilizer N is incorporated into pools with slow turnover times, increasing N stocks. The major part of leached N derives from the mineralization of organic matter rather than directly from applied fertilizer, as has been shown by a number of studies (Addiscott et al., 1991). For example, in a Rothhamsted experiment nitrate leakage declined to half its initial rate only after 41 years without fertilizer application (Addiscott *et al.*, 1991). Similarly, N released from riparian ecotones tends to originate from within the system, while external nitrate input is absorbed. Nitrogen overload and built-up of organic N have led to the hypertrophication of agricultural soils and landscapes, which may continue to release nitrate for decades, even if nutrient inputs were reduced drastically (Addiscott *et al.*, 1991; Steininger *et al.*, 1997; Vagstad et al., 1997). Due to memory effects, buffer zones may also act as N- source long after the pollution of waterways has been abated (Gilbert *et al.*, 1990). Delay of N translocation in subsurface environments may be considerable; e.g., residence times in aquifers range from less than 1 year (karst) to 10^3 years (plains of Northern Germany (Wendland, 1992), though normally maximum residence time in German aquifers is 25 to 40 years (Bouwer, 1995) with an average of 20 years (Isermann and Isermann, 1997). It can be inferred that "system memory", temporary storage and slow transport can delay the emission of excess N into the aquatic system for decades. In the view of long-term sustainability, the transfer of excess nutrients to transitory storage compartments is no solution. While in conventional agriculture microeconomic time preferences and small-scale system boundaries prevail, sustainable agriculture needs to take account of large-scale and long-term effects (Norton, 1995).

Scope of impacts

The environmental impact of nitrate depends on the scalar level under consideration (Isermann, 1993): On a local scale, N emissions may lead to the contamination of groundwater and to the eutrophication and acidification of dystrophic and headwater ecosystems. Headwater streams and their ecotones tend to be particularly sensitive to pollutant inputs (Hamm, 1991). On a regional scale, rivers and lakes are subject to eutrophication, though they often are P limited rather than N limited. In sharp contrast to the majority of temperate-zone lakes, where P is the nutrient that limits primary productivity by algae and other aquatic plants and controls eutrophication, these processes are controlled by N inputs in the majority of temperate-maritime ecosystems (Vitousek *et al*., 1997a).

7.1 Nitrous oxide production

While denitrification may be beneficial for aquatic ecosystems, the production of nitrous oxide due to denitrification leads to problems on a global scale, as nitrous oxide is both a very efficient greenhouse gas (Houghton, 1994) and plays a role in stratospheric ozone depletion (Crutzen, 1970). There is evidence for the emission of nitrous oxide from the entirety of the compartments discussed above (Dowdell et al., 1979, Yoshinari, 1990). Nitrous oxide emissions from soils vary (Freney, 1997). Depending upon fertilizer type 0.07 % to 2.7 % may evalve as N_2O (Eichner, 1990). On the average 0.5-1.5 % (McElroy and Woofsy, 1985) or 1.25 % (Bouwman, 1992) of applied N to agricultural soils may be emitted as N_2O. Subsoil production of nitrous oxide is not known (Rice and Rogers, 1993). In contaminated aquifers, values of 3.4-7.8 kg N_2O $ha^{-1}yr^{-1}$ have been measured (Ronen et al., 1988). Shallow aquifers are supposed to be more likely sources of N_2O than confined aquifers (Rice and Rogers, 1993). It is inferred that aquifers could account for 5 to 10 % of total global nitrous oxide source (Rice and Rogers, 1993), i.e. 10 to 20 % of biogenic N_2O sources could originate from aquifers. Nitrous oxide production in riparian zone aquifers ranged from 0.026 to 3.7 % of N input on Rhode Island (Jacinthe et al., 1998) and 0.65-0.87 % of the input in aquifers in Maryland (Weller et al., 1994). Riparian vegetation thus has a high potential to function as hotspot, inducing nitrous oxide production (Groffman and Gold, 1998), although in many cases riparian vegetation may not emit more N_2O than cropland (Gilliam *et al*., 1997). Rivers and lakes have been observed to emit N_2O as well (Mariotti, 1994; McMahon and Dennehy, 1999). Overall nitrous oxide emissions from rivers, estuaries and continental shelves increase with increasing N loading from 0.3 % to 3 % or even 6 % of denitrification rates; thus approximately 1 % of total N input into these systems may be emitted as N_2O (Kroeze and Seitzinger, 1998). Evidently, the contamination of the subsurface environment with nitrate has the potential for increasing the contribution to atmospheric N_2O (Rice and Rogers, 1993). In fact, direct N_2O emissions (2.1 Tg N) may equal indirect emissions (2.1 Tg N) resulting from agricultural N input into the atmosphere and aquatic systems (Mosier et al., 1998). Thus a (nitrate) water quality problem may be traded for an atmospheric problem (Isermann and Isermann, 1997).

In addition, the loss of nitrate from the field has to be considered as the loss of a resource whose production is linked to the consumption of energy (ca. 47 MJ kg^{-1} N fertilizer) and to the emission of atmospherically active substances. On the average 2500 g CO_2, 10 g N_2O and 1 g CH_4 are emitted to produce 1 kg of N fertilizer (Kaltschmitt, 1997).

7.2. Scale and scope as evaluation criteria

For the evaluation of environmental impact, scale and scope have been forwarded as criteria (Gleich, 1998, Scheringer, 1999). Scope may be defined as the ratio of collateral to intended effects, with crop uptake as the main intended effect of N fertilization. Scope increases with the length and complexity of cause-effect chains. The scale of impact ranges from local/reversible to global/irreversible. The local-global dichotomy indicates to what extent impacts can be attributed to local actors (Norton, 1995; Norton and Ulanowicz, 1992); "reversibility" indicates to what extent and with what ease impacts can be subject to control and remediation. Due to decreasing reversibility and attributability, the larger the scale and scope of emissions, the more problematical they are. To disentangle the impact of agricultural emissions hierarchical, scalar approaches may serve as a heuristic tool (Ahl and Allen, 1996; O´Neill et al., 1989; Wagenet, 1998) and as basis of evaluation.

6. Simulation and prediction of nitrate fate?

Simulation models have been forwarded as tools for the prediction, management and evaluation of agricultural emissions, in particular nitrate. For the prediction of biogeochemical processes on compartment or ecosystem level, no valid general models are available (Hauhs et al., 1996; Oreskes et al., 1994). Variability of the degrees of freedom and the self-modifying character of ecosystems (Kampis, 1991; Lange, 1998) invalidate system descriptions along larger time frames. Accordingly the simulation of (micro-)biological processes e.g., immobilization and denitrification offers particular problems (de Willigen and Neetson, 1985; Marchetti et al., 1997; Stockdale et al., 1997). Moreover, the interaction of scale and physical structure is highly problematic as due to the spatial heterogeneity of ecosystems on all scales, spatial structure is unknowable at any scales of real interest (Beven, 1996). As a consequence transport in conduits (e.g., preferential flow) is unpredictable (Bouma, 1992; Jury and Flühler, 1992; Stagnitti *et al.*, 1995), and upscaling of distributed models is problematic (Blöschl and Sivapalan, 1995). Spatially transferable models have to be calibrated and validated with data from short-term sets, which do not represent the range of natural phenomena (Konikow and Bredehoeft, 1992). Accordingly, short-term extreme events may override average conditions (Petersen et al., 1987), represented by models. Thus an accurate quantitative prediction of N dynamics and nitrate loss from agricultural systems seems impossible (Jury and Flühler, 1992, Richter and Benbi, 1996).

Transition zones present even more severe obstacles to prediction. Variability and heterogeneity in terms of soils, biogeochemistry and water pathways in ecotones are much greater than the additive properties of adjacent resources (Merot and Durand, 1997; Naiman *et al.*, 1988). The non-linearity of retention processes, the intricate physical structure and influence of memory effects (land use legacy) turn riparian zones into singularities (Breckling, 1992), for which a quantitative prediction seems unattainable (Wagenet, 1998). The connection of compartments and ecosystems on the landscape level offers additional problems.

The linkage of fluxes between different compartments is generally not well understood; e.g., the matter transfer between the unsaturated and the saturated zone (Del Re and Trevisan, 1995), and lateral fluxes and the flux of substances between adjacent ecosystems (Grunewald, 1996). Even in detailed, site specific case studies, a mechanistic knowledge of these interactions has not been obtained.

7. A framework for landscape risk assessment

In a framework for sustainable agriculture and in the light of the precautionary principle (O'Riordan and Jordan, 1995; Westra, 1997) system uncertainties as reflected in simulation models for ecosystems need to be acknowledged (Haag and Kaupenjohann, 2000). The concomitant shift from impact-oriented to risk-oriented approaches favors methods which address environmental risks, capacities (Cartwright, 1994) and output potentials and which aim at the identification of problem areas and risky management options. As indicators of (un-)sustainable landscape management budget approaches and simple output potentials are suitable. To indicate the risk of nutrient loss, water and nutrient budgets may be computed. While the compilation of budgets contributes little to the understanding of a system (Stockdale *et al.*, 1997), budgets hint at desequilibria long before measurement or other methods indicate elevated soil concentrations or matter loss with confidence (Baccini and von Steiger, 1993). Output potentials for larger temporal and spatial scales may be more reliable (Stockdale *et al.*, 1997), as larger areas like watersheds tend to behave more determinate than smaller ones (Corre et al., 1996; Groffman *et al.*; 1987 and Wagenet, 1998). The budget approach, however, takes no account of the spatial setting into which agricultural sites are embedded. Budgets should thus be part of a larger screening scheme, which could encompass the following categories of risk potentials:

<u>Site specific risk</u> which is represented by simple, physical factors and which is linked to the soil, topography and climate (see e.g., Marks and Alexander, 1992; Gäth and Wohlrab, 1994; Hölting et al., 1995 for Central Europe). For nitrate leaching the frequency of soil water exchange as a function of water surplus and texture class is a useful indicator (Gäth and Wohlrab, 1994).

<u>Agricultural activity risk</u> is assessed with budget approaches, indicating long-term risks and providing hints at potential disequilibria (Baccini and von Steiger, 1993; Isermann and Isermann, 1997; Umweltbundesamt, 1997).

<u>Headwater contamination risk</u> (local risk): The spatial setting of an agricultural site and of agricultural landscapes are to be accounted for. Corridors, their proximity to agricultural sites and their propensity to matter input deserve particular attention: Transport in conduits tends to

increase scale and scope as conduits usually form part of a hierachical, unidirectional networks. Cartographic approaches may indicate the abundance and proximity of corridors and the abundance of retention compartments within a landscape section. Quantitative measures for landscape pattern (Gustafson, 1998) and GIS applications may facilitate operationalisation.

Regional and global scale risk is assessed qualitatively, based on the criteria of scale and scope and quantitatively, based on life cycle assessment (Vito, 1998), which e.g., may indicate overall global warming potential due to N fertilization.

Such a screening approach evaluates risk potentials, while it leaves out of consideration actual matter fluxes. The approach is thus restricted to the identification of key contributor and problem areas; it may be followed by site specific process studies or monitoring of environmental quality.

8. Remediation concepts

System approaches are advocated (Ikerd, 1993) focussing on nutrient cycles (Hendrix *et al*., 1992; Magdoff *et al*., 1997), which should be both tight with regard to spatial and temporal scales and close with regard to matter loss, ensuring a maximum of reversibility/controllability. The plot is the valve, where losses ultimately occur, hence optimization of cycles on the plot scale is imperative. As the plot is part of a hierarchy of landuse and production systems, aside with the plot level, the farm and the regional level also call for optimized cycles.

Detachment of (quasi-industrial) dairy and livestock production from the spatial extension of farmland (Steinfeld et al., 1996) imposes major constraints on cycling approaches: While plant production reaches an N efficiency of 57 %, overall agricultural N efficiency is only 25 %, as 85 % of plant production, together with imported feeds, are utilized in animal production (Isermann and Isermann, 1998). With the carrying capacity of agricultural land being overstrained, fields and grassland frequently function as waste-dumps for excess nutrients from livestock (Isermann and Isermann, 1997). As animal production dominates the agricultural N cycle, it becomes a key driver as to N overload.

A shift away from linear concepts, in which wastes (like excretions in animal production or nitrate in plant production) are considered the norm should lead to integrated systems targeting total throughput, i.e. systems making optimal use of inputs and mimicking natural cycles. Such a concept of "zero emission" has recently been developed for industry (Mshigeni and Pauli, 1996); it could also be useful for industrial agriculture.

The optimization of production systems on farm and larger scales remains within the realm of sectoral approaches. While in Central Europe fertilization accounts for 83 % of total net anthropogenic N input (Howarth *et al*., 1996), agricultural production is but one subsystem in regional N metabolism. Regional approaches which assess matter fluxes among and matter budgets of different sectors (German Council, 1996) are a way of addressing and tackling disequilibria on larger scales. Tools for the assessment of regional metabolism (Baccini and

Bader, 1996; Baccini and Brunner, 1991) and quantitative examples, including N fluxes and budgets on a regional level, have been developed recently for Central Europe (Baccini and Bader, 1996; Brunner and Baccini, 1992; Henseler et al., 1992). The identification of key contributors and key fluxes may guide optimization on an integrated, regional level.

9. Conclusions

Different landscape elements exert control on the flux and fate of excess nutrients such as nitrate. The conceptual approach, which distinguishes retention compartments and corridors and which provides for the scalar assessment of risks induced by emissions can be adapted to other agricultural inputs like pesticides. Retention of nitrate on the local scale, ranging from the field to the stream, has been shown to be of limited and/or of uncertain extent in many compartments on the way from the field to the stream. Storage of N in vegetation, soil organic matter and groundwater may delay the emission of excess N for decades, masking past and present N disequilibria and overloads. On the regional level , elimination in rivers and lakes may contribute to the reduction of N discharge to the sea. Notwithstanding, N discharge has experienced a manifold increase in comparison to preindustrial times, leading to the eutrophication of coastal waters. Denitrification and the concomittant production of N_2O together with emissions arising from fertilizer production may shift the issue of N overload from a terrestrial-aquatic to an atmospheric problem.

Current agricultural practices and end-of-the-pipe solutions (e.g., buffer zones) seem rather unsustainable in view of the unpredictability of matter fluxes, of the uncertainties considering retention behavior of landscape elements, of the often limited, partly non-renewable retention potentials, and of the only temporary storage of N in landscapes. Instead of short-term, small-scale considerations, an integrated system approach should be pursued, which envisages tight and close cycles and the optimization of N fluxes and budgets at site, farm and regional level. On the latter, both the fluxes induced by the agricultural production and the agricultural sector as a whole and the fluxes arising from other human activities need to be assessed and reconciled.

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Summary

Models for the representation of ecological systems? The validity of experimental model systems and of dynamical simulation models as to the interaction with ecological systems

Models, defined as reconstructions of natural systems with analogies, guide the observation and description of and the interaction with complex ecological systems. Conventionally, scientific models obey an image of positivist, normal (in Kuhn´s sense) science, which claims to posses a privileged exo-perspective and to produce abstract solutions for well-defined problems, reducing uncertainty and contributing to the production of universal knowledge. As to many environmental systems and issues, however, uncertainty is irremediably high, while specific interests, values and norms as determinants of contingent, non-equivalent system descriptions gain importance. For such issues, the image of post-normal science has been developed.

In this thesis features and limitations of models in the environmental sciences are investigated. Background of the thesis was an interdisciplinary research project which pretended to operationalize the notion of ecological sustainability for agricultural plant production. Particularly, experimental model systems (I) and simulation models (II) are critically investigated in this thesis with respect to model paradigms, analogy assumptions and the role of models for man-environment interactions. The terrestrial nitrogen cycle and its anthropogenic modifications serve for the illustration of model concepts and the limits to the establishment of cause-effect relationships in non-manipulated ecological systems (III). The use of models in science for policy is evaluated in the context of (epistemic) uncertainty, the precautionary principle, the concept of post-normal science and the discursive opening of the science system (IV).

Basis and material of this thesis were (a) empirical work from the environmental sciences, (b) contributions to ecosystem theory and models in the earth sciences, (c) philosphical work on the role/status of experiments and of models in the natural sciences and (d) work in the fields of science research and the sociology of science, which address different scientific practices and different forms of knowledge production.

I. Experimental model systems

Experimental model systems are materially and conceptually closed systems, which allow for the investigation of a limited number of parameters. As material systems they are bounded in time and space and they are closed and controlled as to matter, energy, thermodynamics and information. Empirical-experimental model systems posses a material component which is encoded into a formal, numerical-mathematical system in the course of the measurement of determined parameters. The transfer of statements derived from

model systems to open, natural systems with biotic components is critically discussed (see II for the image of open ecological systems).

II. Dynamical simulation models

The discovery of complexity associated with the development of the theory of dynamical systems allowed for the simultaneous handling of a large number of interrelated parameters. The success of dynamical systems as to the representation and management of technical (allopoietic) systems presumably has contributed to the fact that the dynamical system has become *the* paradigm for the representation of complex systems. For example, technical analogies and machine metaphors become evident in the program of ´ecological engineering´.

Dynamical systems are conceptually closed systems, comprising a defined, closed set of parameters. Dynamical systems are based on the notions of abstract state and identity in time and frequently it is tacitly assumed that the abstract state represents the essence of the represented system. Dynamical systems are ahistorical systems without distinguished positions in time such as the past or the now. Past and present values of the state variables can be computed as a function of the external, universal parameter time.

Against the background of the paradigm of selfmodifying systems of G. Kampis, dynamical systems are critically investigated in this thesis. The two traditions which face each other here can be characterized by the opposition of ´state´ versus ´processes´ and ´being´ versus ´becoming´. The contrast between static, closed conceptions, which are at the heart of dynamical but also of experimental model systems, and of an image of ecosystems as conceptually open systems is discussed. Major points are the evolutionary openness of ecological systems, the internal production of new variables and the emergence of system level properties, which relativize and make appear contingent any separation and abstraction of the dynamical part of an ecological system from contingent features (´noise´) and from the environment of the system. It is hypothesized that in contrast to physical systems with a stable setting (e.g., in astronomy on human scales) in ecosystems agents with rule-making capacities exist, which possess the potential to modify rules on-line (within the boundaries of physical and chemical laws) according to changes in their environment.

The status of parameters and variables deserves peculiar attention: While some parameters in simulation models may possess a material-real reference (in the spirit of entity realism), many parameters are derived from mathematical or practical needs. Due to such parameters of convenience and to the exogenous and endogenous modification of parameters in natural systems the divergence between the closed dynamical system and its external reference, the natural system, tends to increase. Accordingly, neither the operational (empirical) nor the conceptual validation of the closed dynamical system as representations of conceptually open systems is possible. The lack of predictive capacity (particularly on larger temporal scales) and the impossibility of validation render dynamical models deficient tools for the reduction of uncertainty as to the future behavior of complex real-world systems.

III. The nitrogen example

The terrestrial nitrogen cycle and its anthropogenic modification serve for illustration in the various parts and are considered in more depth in a separate part. The long-term retention capacity of landscapes for excess nitrogen from agriculture is addressed; different model concepts and their limitations are compared and related to different forms of uncertainty and to the precautionary principle.

IV . Uncertainty and post-normal science

Scientific uncertainty derives among others from the impossibility to generalize existent models and from the indeterminacy of self-modifying, ecological (and cognitive) systems. When the shaping of man-environment interaction is on the agenda, a peculiar form of uncertainty arises, epistemic uncertainty: different distinctions and different observer perspectives lead to different, non-equivalent descriptions of the same system. This holds both for scientific descriptions (e.g., the different perspectives of system ecology and population ecology) and for real-world descriptions by local agents and stakeholders, which posses a specific set of distinctions, interests and values. In view of the irreducible uncertainty and perspectivity governing the identification and description of ´relevant´ phenomena and parameters, the question arises which paradigms for the description of complex systems and the treatment of risk and uncertainty are valid. Depending upon what is at stake, validation may be conceived as a disciplinary, transdisciplinary and (particularly in science for policy) transscientific task. In the latter, a notion of validation as the establishment of legitimacy may be useful. Validation at the interface of science and society would accordingly be conceived as a communication and negotiation process instead of an objective scientific method. Drawing from recent risk research for such issues the image of post-normal science is developed, which encompasses the discursive opening of scientific (sub-)systems. A corresponding role for models and modelling is sketched. While in the science system models usually are regarded from the point of view of representation or prediction, in the framework of science for policy the role of models as communication instruments would have to be stressed. Models would thus serve for the synthesis, communication and visualization of scientific knowledge, for the integration of scientific and object knowledge and for learning to interact with complex systems.

Zusammenfassung

Modelle für die Repräsentation ökologischer Systeme? Zur Validität von Modellsystemen und von dynamischen Simulationsmodellen bei der Interaktion mit ökologischen Systemen

Modelle, definierbar als Rekonstruktionen natürlicher Systeme mittels Analogien, strukturieren die Beobachtung und Beschreibung von und die Interaktion mit komplexen ökologischen Systemen. Wissenschaftliche Modelle sind üblicherweise einem Bild positivistischer (im Kuhn´schen Sinn) normaler Wissenschaft verbunden, die den Anspruch erhebt, aus privilegierter (Exo-)Perspektive abstrakte Lösungen für abgegrenzte Probleme hervorzubringen und dabei universelles Wissen zu produzieren. Im Gegensatz dazu macht sich post-normale Wissenschaft (in Anlehnung an Funtowicz und Ravetz) Systeme zum Gegenstand, in denen Ungewißheit (in ihren verschiedenen Formen) hoch ist und bei deren Beschreibung Interessen, Werten und Normen eine irreduzible Bedeutung zukommt.

In dieser Arbeit, die in einen interdisziplinären Forschungsverbund eingebettet war, der sich die Operationalisierung des Begriffes ökologischer Nachhaltigkeit für die landwirtschaftliche Pflanzenproduktion zum Ziel gesetzt hatte, werden Charakteristika und Begrenzungen von umweltwissenschaftlichen Modellen untersucht. Im Zentrum stehen Modelle, die auf Analogien zwischen natürlichen Systemen und experimentellen Modellsystemen (I) bzw. zwischen natürlichen und dynamischen Systemen (II) beruhen. Dabei werden Modellparadigmen und die Rolle von Modellen bei der Gestaltung von Mensch-Umwelt Interaktionen kritisch geprüft. Am Beispiel des Stickstoffkreislauf und seiner anthropogenen Modifikation werden Modellansätzen und Grenzen der Ableitung von Ursache-Wirkungsbeziehungen in nicht-manipulierten ökologischen Systemen illustriert (III). Die planerische Verwendung von Modellen bzw. der Einsatz von Modellen in der Politik ("science for policy") wird im Kontext von Ungewißheit, Vorsorgeprinzip, post-normaler Wissenschaft und einer diskursiven Öffnung des Wissenschaftssystems neu bestimmt (IV).

Grundlage und Material der vorliegenden Dissertationsschrift waren (a) empirische umweltwissenschaftliche Arbeiten, sowie Beiträge zur Ökosystemtheorie und zur Modellbildung in den Geowissenschaften, (b) wissenschaftsphilosophische Arbeiten zum Status von Experiment und Modell in den Naturwissenschaften und (c) Arbeiten aus der Wissenschaftsforschung und -soziologie, die sich mit unterschiedlichen wissenschaftlichen Praktiken und unterschiedlichen Formen der Wissensproduktion auseinandersetzen.

I. Experimentelle Modellsysteme

Experimentelle Modellsysteme sind materiell und konzeptionell geschlossene Systeme, die die Untersuchung einer begrenzten Anzahl von Parametern ermöglichen. Als materielle

Systeme werden sie räumlich und zeitlich abgegrenzt und sie werden stofflich, energetisch, thermodynamisch und informatorisch kontrolliert bzw. geschlossen. Experimentell-empirische Modellsysteme verfügen somit über eine materielle Komponente, die im Zuge der Messung festgelegter Parameter in ein formales, numerisch-mathematisches System kodiert wird. Die Übertragbarkeit von Aussagen, die mittels Modellsystemen gewonnen wurden, auf nicht-geschlossene, natürliche Systeme mit biotischen Komponenten wird kritisch diskutiert (s. u. II).

II. Dynamische Simulationsmodelle

Die Entdeckung der Komplexität in Verbindung mit der Entwicklung der Theorie dynamischer Systeme hat die simultane Behandlung einer hohen Zahl miteinander verknüpfter Parameter ermöglicht. Der Erfolg dynamischer Systeme bei der Repräsentation und dem Management technischer Systeme hat vermutlich entschieden dazu beigetragen, daß dynamische Systeme zu *dem* Paradigma für die Repräsentation komplexer Systeme avanciert sind; so werden technische Analogien und Maschinenmetaphern z.B. im Programm eines "Ecological Engineering" augenfällig.

Dynamische Systeme sind konzeptionell geschlossene Systeme, die auf der Vorstellung von abstraktem Zustand und Identität in der Zeit fußen. Dabei wird meist implizit angenommen, der abstrakte Zustand repräsentiere die Essenz des abgebildeten Systems. Dynamische Systeme verfügen über ein definiertes, geschlossenes Set von Parametern und sie sind als geschichtslose Systeme ohne ausgezeichnete Zeitstellen wie Vergangenheit und Gegenwart konzipiert. Vergangene und zukünftige Werte der Zustandsvariablen können, bei Kenntnis des abstrakten Zustandes, als Funktion des (externen, universellen) Parameters Zeit berechnet werden.

Vor dem Hintergrund des Paradigmas der selbstmodifizierenden Systeme von G. Kampis werden in der vorliegenden Arbeit dynamische Systeme kritisch reflektiert. Dabei treffen zwei unterschiedliche Traditionslinien aufeinander, die mit den Schlagworten "Zustand" versus "Prozeß" bzw. "Sein" versus "Werden" charakterisiert werden können. Der Gegensatz zwischen statisch-geschlossenen Konzeptionen, die dynamische aber auch experimentelle Modellsysteme prägen, und einem Bild von ökologischen Systemen als konzeptionell offenen Systemen wird diskutiert. Wesentlich sind dabei die evolutionären Offenheit ökologischer Systeme, die interne Produktion neuer Variablen und die Emergenz systemarer Eigenschaften, die wiederum die Abtrennung und Abstraktion des dynamischen Teils eines ökologischen Systems von kontingenten Anteilen ("Rauschen") und von der Umwelt des Systems als relativ und kontingent erscheinen lassen.

Im Gegensatz etwa zu physikalischen Systemen mit stabilem Setting (z.B. in der Astronomie) gibt es in ökologischen Systemen Akteure, die, -im Rahmen physikalischer und chemischer Grenzen - über das Potential verfügen, Regeln in Abhängigkeit von sich verändernden Umweltkontexten on-line zu modifizieren.

Der Status von Parametern und Variablen in Modellen verdient besondere Beachtung: Während etwa einige Parameter und Variablen eine material-reale Referenz (im Sinne eines Entitätenrealismus) aufweisen können, fußen viele Parameter auf mathematischen oder praktischen Erfordernissen; solche Parameter besitzen konventionalen Charakter. Aufgrund der Vielzahl konventionaler Parameter und aufgrund der exogenen und endogenen Modifikation von Parametern in natürlichen Systemen wächst tendenziell die Divergenz zwischen den geschlossenen, dynamischen Systeme und ihrer externen Referenz, den natürlichen Systemen. Weder eine operational-empirische noch eine konzeptionelle Validierung der geschlossenen dynamischen Modelle als Repräsentationen für konzeptionell offene Systeme ist möglich. Mangelhafte Vorhersagegüte bzw. prognostische Fähigkeiten (insbesondere auf größeren zeitlichen Skalen) und die grundsätzliche Unmöglichkeit einer naturwissenschaftlich-technischen Validierung führen dazu, daß dynamische Systeme Ungewißheit hinsichtlich des Verhaltens komplexer natürlicher Systeme nicht ausräumen können.

III. Beispiel Stickstoff

Der terrestrische Stickstoffkreislauf und seine anthropogene Modifikation dienen den verschiedenen Teilen dieser Arbeit als Anschauungsmaterial und werden in einem gesonderten Teil vertieft: Das langfristige Retentionsvermögen von Landschaften für überschüssigen Stickstoff und unterschiedliche Modellkonzepte und ihre Limitationen werden diskutiert und zu Formen der Ungewißheit und zum Vorsorgeprinzip in Beziehung gesetzt werden.

IV. Ungewißheit und post-normale Wissenschaft

Wissenschaftliche Ungewißheit beruht u.a. auf der mangelnden Generalisierbarkeit von Modellen und auf der Nicht-Determiniertheit selbstmodifizierender natürlicher Systeme. Bei der Gestaltung nachhaltiger Mensch-Umwelt Interaktionen kommt eine weitere, epistemisch-ethische Form der Unbestimmtheit hinzu: Verschiedene Unterscheidungen und Perspektiven des jeweiligen Beobachters führen zu unterschiedlichen, nicht-äquivalenten Beschreibungen desselben komplexen Systems. Dies gilt sowohl für wissenschaftliche Beschreibungen (z.B. unterschiedliche Perspektiven von Systemökologie und Populationsökologie), mehr aber noch für lebensweltliche Beschreibungen z.B. durch lokale Akteure und Stakeholder, die über spezifische Ensembles von Differenzen, Interessen und Werten verfügen. Angesichts von Ungewißheit und Perspektivität bei der Identifikation "relevanter" Phänomene und Parameter stellt sich die Frage, welche Paradigmen zur Beschreibung von komplexen Systemen und zur Behandlung von Risiken und Ungewißheit disziplinäre, transdisziplinäre und (bei der planerischen Verwendung von Modellen) transwissenschaftliche Validität beanspruchen können. Dabei mag ein Begriff von Validierung fruchtbar sein, der Validierung als Etablierung von Legitimität betrachtet. Validierung im Zwischenbereich von Natur-/Komplexitätswissenschaften und Gesellschaft wäre demnach als Kommunikations- und Aushandlungsprozeß und nicht als objektivierbare, wissenschaftliche Methode zu konzipieren. In Anlehnung an neuere Befunde der Risiko- und Wissenschaftsforschung wird das Bild einer post-normalen Wissenschaft entwickelt, das eine diskursive Öffnung geschlossener wissenschaftlicher (Sub-)Systeme beinhaltet. Eine Neubestimmung der Rolle von Modellen und

Modellbildung in einem post-normalen Rahmen wird skizziert. Während im System der Wissenschaft Modelle üblicherweise unter dem Gesichtspunkt von Repräsentation und Prognose betrachtet werden, wäre im Rahmen einer "Science for policy" die Rolle von Modellen als Kommunikationsinstrument hervorzuheben, sei es bei der Synthese, Kommunikation und Visualisierung wissenschaftlichen Wissens, bei der Integration von wissenschaftlichem und Alltags/Objektwissen oder für das Erlernen des Umgangs mit komplexen Systemen.

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