17 System Dynamics in Transdisciplinary Research for Sustainable Development

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Abstract

Problems in research for sustainable development are often complex, ill-defined, dynamic, and intersectoral, calling for a transdisciplinary approach, that is, an approach that enables researchers to both cross disciplinary boundaries and interact with stakeholders from society. Transdisciplinary research for sustainable development, however, faces specific challenges or 'traps', in particular the 'ideographic trap' and the 'theory trap', which are rooted in the fact that this type of research is necessarily bound to a specific context. We argue that system dynamics complies with the majority of epistemic requirements of transdisciplinarity and, as a consequence, is a valuable instrument for transdisciplinary research. Moreover, the use of system dynamics may offer genuine contributions to overcoming the above-mentioned traps. Indeed, system dynamics has a potential for generalisation, making it possible to overcome the 'ideographic trap'; and a system dynamics model necessarily embodies a (causal) theory of the explored system. Using a case study aiming to improve understanding of collective irrigation management in Kyrgyzstan, we illustrate how the use of system dynamics helped to deal with the complexity of the problems under research, while also enabling participation by involved stakeholders on the one hand, and integration of their knowledge and vision of sustainable development on the other. We summarise the generalisable and theoretical findings that also emerge from the case study. Finally, we conclude that system dynamics could be used more frequently in transdisciplinary research, in particular for participatory analysis of dynamic, complex problems and the development of options to overcome these problems.

Keywords: Transdisciplinary research; system dynamics; research for sustainable development; modelling; collective irrigation management; Kyrgyzstan.

17.1 Introduction

Societally relevant problems dealt with in research for sustainable development are often complex, ill-defined, dynamic, and intersectoral, calling for a transdisciplinary approach (Kates 2001; Wiesmann et al 2008), that is, an approach that enables researchers both to cross disciplinary boundaries and work with involved stakeholders (Hirsch Hadorn et al 2008; Ngana et al 2010). In particular, methods and instruments are required to analyse and anticipate dynamic pathways that a complex system may follow, as well as to make explicit the different viewpoints of the stakeholders involved and integrate them (Agrawal 2001; Clark et al 2004; Elzinga 2008).

In the first part of the present article we argue that system dynamics as a modelling approach for the analysis of complex dynamic systems (Forrester 1961) meets a considerable number of epistemic requirements for transdisciplinary research (Wiesmann et al 2008), and that, as a consequence, system dynamics is a valuable instrument for transdisciplinary research. System dynamics is open to incorporating knowledge from different disciplines as well as various forms of knowledge held by different stakeholders (Cassel-Gintz 2004). As such, it enables integration, one of several conditions for transdisciplinary research (Pohl and Hirsch Hadorn 2007).

In the second part, we show that system dynamics may provide genuine contributions to transdisciplinary research for sustainable development. Indeed, by analysing the causal structure of a problem in a specific context, a system dynamics study may provide *generalisable* knowledge that can be used in other contexts. System dynamics therefore helps to overcome the ‘ideographic trap’ that researchers face in research for sustainable development, that is, the tendency to consider that each case is unique and generalisation is impossible (Wiesmann and Messerli 2007; Krohn 2008). Moreover, as a system dynamics model embodies a theory of the problem to be studied, it provides a means of *theory building and theory testing* related to an observed behaviour in a specific context, thus contributing to overcoming the ‘theory trap’ – that is, the tendency in research for sustainable development to miss opportunities offered by innovative disciplinary theories (Wiesmann and Messerli 2007).

We illustrate how system dynamics contributes to overcoming these traps by referring to a system dynamics study of collective irrigation management in Kyrgyzstan (Gallati 2008a, 2008b). The case study used system dynamics to provide, among others, a dynamic feedback model that enabled researchers and stakeholders from society to analyse the conditions under which successful and unsuccessful cooperation may result. Potentials and limitations of this approach with regard to overcoming the above-mentioned traps are discussed.

17.2 Transdisciplinary research

Transdisciplinary research is understood here as research that "addresses the knowledge demands for societal problem solving regarding complex societal concerns" (Hirsch Hadorn et al 2006). This implies cooperation within the scientific community, referring to and integrating a variety of disciplines, and a participatory research design. The concepts of transdisciplinary research and research for sustainable development are closely related; the two terms are sometimes even used interchangeably. Thus transdisciplinary research can be considered a type of research needed to meet knowledge demands for sustainable development (Scholz et al 2006).

Transdisciplinary research takes into account the complexity of the problems at stake, the diversity of perspectives with regard to these problems, the tension between contextuality and generality, and the value dimension of research for sustainable development. Within a transdisciplinary research process, it is necessary to i) grasp (and reduce) the complexity of a problem, ii) take into account the diversity of real-world and scientific perceptions, iii) link abstract (general) and case-specific knowledge, and iv) take into account multiple social goals and conflicting values (Pohl and Hirsch Hadorn 2007). Methods applied in transdisciplinary research should follow these principles and, in particular, should provide a potential for integration. A comprehensive analysis of the epistemic requirements for transdisciplinary research has been undertaken by Wiesmann and colleagues (2008) and is summarised below in Table 1.

17.3 System dynamics as a potential instrument for transdisciplinary research

System dynamics as an approach to understanding and analysing complex dynamic systems originated in the late 1950s (Forrester 1961) and has been applied since to numerous problems in society, management, and ecology

(Ford 1999; Sterman 2000) in problem-oriented research. Later, participatory modelling (Vennix 1996) and modelling for learning organisations (Morecroft and Sterman 1994) came into the focus of the system dynamics method, leading to a comprehensive reflection on process design and valuation (Pidd 2004).

As a modelling approach, system dynamics relies on three constituents: the concept of feedback loops, computer simulation, and the notion of 'mental models' and participatory involvement of stakeholders. System dynamics claims that a system can be described by state variables and influencing actions, which, in turn, change the state of the system (Lane 2000). These feedback loops involve processes of accumulation and drainage, causing delays and non-linearities in the system.

Computer simulation, as the second element, is needed to assist humans in capturing the inherent dynamics of a feedback model. It has been shown that although humans can conceptualise feedback loops, they lack the cognitive capability to deduce the consequent dynamic behaviour without assistance (Sterman and Sweeney 2007). Computer simulation is essential in particular for uncovering unanticipated side-effects (Sterman 2000) and counterintuitive behaviour.

The third element of system dynamics, finally, has to do with the involvement of the so-called 'problem owners' (i.e. stakeholders) in the modelling process. It has been recognised that most important information about social situations is held only as 'mental models' and not in written form (Forrester 1994). These mental models, which are the basis of organisational decision-making (Lane 2000), are complex and subtle, involving hard, quantitative information as well as more subjective or judgemental aspects of a given situation. To elicit these aspects and to stimulate learning experiences that may gradually change mental models, allowing to better manage the system, the modelling process has to be designed in a participatory way. Building on these traits, system dynamics has the potential to be used in participatory decision-making and decision support (Van den Belt 2004).

As a consequence, system dynamics studies are focused on understanding, not on prediction. The goal of a system dynamics policy study is to understand those interactions in a complex system that are leading to a problem, and understand the causal structure and dynamic implications of policy changes intended to improve the system's behaviour (Richardson 1991).

A model offering a plausible representation and hence explanation of an observed behaviour is considered to embody a theory of these phenomena (Lane 2000). A system dynamics model thus belongs to the category of causal, theory-like models, which – contrary to purely correlational models – are aimed at illustrating and explaining system behaviour by unravelling causal relations (Barlas 1996). In this process, explicitly addressing, illustrating, and discussing causal relations can form an important element of participatory negotiations in a concrete problem setting (Cassel-Gintz 2004).

Building on the characteristics of system dynamics outlined above, we show in Table 1 that system dynamics complies with most requirements of transdisciplinary research and, consequently, is a valuable candidate for the 'toolbox' of transdisciplinary research methods (Scholz and Tietje 2002; Bergmann et al 2010). The requirements are formulated according to the propositions on transdisciplinary research advanced by Wiesmann and colleagues (2008).

Having shown that system dynamics is a possible instrument for transdisciplinary research, we want to emphasise that there are also other integrated systems-modelling paradigms to investigate complex dynamic problems. Among them, complex adaptive systems or multi-agent systems, where a large number of individual components (or agents) interact and adapt (Holland 2006), have recently received growing attention and have been applied to numerous problems in research for sustainable development (Janssen 2002; Parker et al 2003; Bousquet and Le Page 2004). This is not the place for extensively comparing system dynamics with multi-agent systems. We consider these two paradigms as complementary: while system dynamics focuses on an aggregate system level, (possibly) embodying a high level of feedback complexity (Forrester 1994), the multi-agent systems approach focuses on a micro (agent) level, with macro (systems) properties emerging from agent interaction at the micro level.[3]

17.4 How system dynamics helps to deal with the 'ideographic' and 'theory' traps

Beyond this general compliance of system dynamics with the epistemic requirements of transdisciplinary research, system dynamics can make genuine contributions to sustainability research in at least two ways. We argue that these contributions relate, first, to the potential of system dynamics for

Table 1

Compliance of system dynamics (SD) with the epistemic requirements of transdisciplinary research (TR). Figures in brackets refer to the propositions on transdisciplinary research advanced in Wiesmann et al 2008.

	Transdisciplinary research (TR)	System dynamics (SD)
Scope and relevance	Complex problems in the life-world (2)	Complex, messy (ill-structured) problems
Knowledge forms	Systems knowledge providing evidence for empirical questions (4) Target knowledge (4) identifying practices and goals better suited for achieving sustainable development Transformation knowledge about how to change existing practices (4), learning, and experimental implementation	Causal explanation (theory) of the system consistent with observed reference modes of problematic behaviour Policy analysis stimulating learning processes regarding the system's behaviour Simulation-supported interactive learning environments enabling virtual implementation
Sources of knowledge	Relevant bodies of knowledge are determined during the research process (4), including knowledge produced in societal fields as well as scientific knowledge (1).	Modelling refers to different sources of knowledge identified in the course of the process: mental database (mental models), written database, and numerical database.
Contextuality and generality	Shaped by concrete problem contexts, results are basically valid for these contexts. Generality is aimed at by providing transferable insights, models, and approaches; transfer to other contextual settings requires careful validation and adaptation (5).	The modelling process seeks to solve a concrete problem and therefore has an operational (contextual) focus. Generalised ('generic') models can be transferred and adapted to other contexts if the causal mechanisms and the observed modes of behaviour are the same.
Process	Recursive processes (3)	Iterative modelling process

generalisation, and second, to the fact that a system dynamics model embodies a (causal) theory of the system. Due to these characteristics, system dynamics may help to overcome the so-called 'ideographic' and 'theory' traps in research for sustainable development (Hurni and Wiesmann 2004; Wiesmann and Messerli 2007).

As a normative process which, as such, involves the setting and prioritising of values, sustainable development is bound to concrete societal contexts. Each of these contexts provides a unique case, shaping not only the value focus but also the system definition. This characteristic of sustainability sets

Design and management of research process	Perspectives and knowledge of various disciplines and stakeholders are to be integrated from the beginning (8). The participatory process has to be carefully structured to enable mutual learning (7); a balance needs to be found between phases of collaboration (with defined output) and (multi)disciplinary contributions (10).	Perspectives and knowledge of the stakeholders (mental models, problem identification) are to be integrated from the beginning. The participatory process is to be carefully structured with regard to knowledge elicitation, phases, roles, and outputs.
Values and uncertainties	Dealing with values and uncertainties – a core problem of TR – requires a mutual learning attitude with sufficient time allocated, broad ownership, and reflexivity of the process (9).	SD claims to provide a method for a transparent discussion of the individuals' perspectives (including values); uncertainties (with regard to causal structure and data) are taken into account by analysing alternative formulations.
Evaluation, quality control, and validation	Quality control includes process design (integration and collaboration of disciplines and stakeholders, recursive process design) and output to scientific knowledge and societal problem handling (12).	Validation is a key issue in modelling; it is seen as a process of building confidence in the model together with the stakeholders.
Valorisation and implementation	Research is embedded in the life-world of the actors in order to increase the effectiveness of the transdisciplinary process.	Orientation towards implementation calls for involving participants in the modelling process as much as possible.
Competence profile of the research team	Combines specialisation in transdisciplinary methods with high-quality disciplinary contributions (6).	Combines special competence in modelling and process design with high-quality disciplinary contributions.

limits to generalisation in sustainability research and is referred to as the *ideographic trap* of sustainability.

The majority of productive theories in the natural and social sciences are disciplinary theories with a specified area of validity. Because it seeks to address complex real-world problems, sustainability research is often poorly linked to innovative discourses in the potentially involved disciplines. This limited capability of sustainability research to relate to innovative disciplinary theories is referred to as the *theory trap* of sustainability.

The potential of system dynamics for generalisation is rooted in the fact that a system dynamics model provides a transparent, consistent causal description of the underlying processes, and, as such, a theory of the system. In system dynamics literature, the aspiration to provide generalisable insights materialised in the concept of 'generic models' (Lane and Smart 1996).[4] Generic models can be understood as the distilled form of a system dynamics model focusing on the causality and interactions of the feedback loops and the nature of the dynamic behaviour generated, rather than on the details of an operational model. To be termed generic, a model has to be validated for a specific context, and it has to be reduced to a minimal structure (Forrester 1968; Lane and Smart 1996).

Such generalised (generic) system dynamics models offer a transparent means of transferring and adapting insights between different contexts, and can thus contribute to overcoming the 'ideographic trap'. Models can be transferred to other contexts, however, only if the causal mechanisms and the observed modes of behaviour are the same. Hence, the conditions under which a transfer to other contexts is appropriate need to be analysed very carefully. Although this may seem to be a limitation for practical purposes, it can also be considered a unique opportunity to test and further advance the understanding of a particular problem.

As we have pointed out, the potential of system dynamics to address the 'theory trap' is related to the fact that a system dynamics model embodies a theory of the system, and, as such, contributes to theory building and testing. However, to bring this potential of system dynamics to fruition, a proper modelling process needs to refer to and include existing (disciplinary) theories that are capable of describing parts of the problem. On the other hand, the modelling process may also challenge these theories and, potentially, stimulate further disciplinary research. This, however, is only possible if a system dynamics approach is appropriate, that is, if a problem can be properly described i) at an aggregate level and ii) by state variables and influencing actions acting on these state variables.

17.5 System dynamics modelling in a collective irrigation system in Kyrgyzstan

To illustrate the potential of system dynamics for overcoming these two traps, let us describe a case study of collective irrigation management in a rural community in Kyrgyzstan (for full details of the study, see Gallati

2008a). As in virtually all farming areas worldwide, irrigation is a vital condition for increasing agricultural productivity and for improving food security. A farmer-managed collective irrigation management system has been in operation for several decades (Gallati 2008a) but is facing a number of problems that are typical of these systems, in particular deterioration of irrigation infrastructure, insufficient contributions by the users, free-riding in water abstraction, and inequity between upstream and downstream users (Vermillion and Sagardoy 1999). In the study area, irrigation infrastructure has deteriorated seriously in the past 15 years, and farmers have been complaining about insufficient contributions by a large proportion of users (Gallati 2008a). The study we analyse here was, therefore, aimed at developing a systems approach in order to better understand the conditions and the dynamics of successful and unsuccessful cooperation (Gallati 2008b).

A dynamic model was created which incorporated theoretical evidence relating to collective action in general, and to management of common property resources in particular. It also included local farmers' perceptions in relation to important influencing factors affecting cooperation in collective irrigation management. Building on theories of collective action advanced in the social sciences (Granovetter 1978; Schelling 1978) as well as on scientific evidence on common property resources management and collective irrigation management (Wade 1988; Gardner et al 1990; Ostrom 1990; Tang 1992; Lam 1998), the model sought to contribute to overcoming the 'theory trap'. By integrating these findings into a (dynamic) feedback structure with the potential for generalisation to other contexts, the model intended to contribute to overcoming the 'ideographic trap'. The model was applied and validated for a specific context in Saz, Kyrgyzstan, providing insights for this particular situation.

The model describes the dynamics between cooperators and non-cooperators, taking into account the effect of their (joint) contribution on the performance of the irrigation system and, as a consequence, on water availability (Figure 1); the model was developed based on a general critical mass model of collective action (Granovetter 1978; Schelling 1978; Oliver and Marwell 2001) and insights on major influencing factors specific to irrigation and to common property resources management (Wade 1988; Gardner et al 1990; Ostrom 1990; Tang 1992; Lam 1998). In the proposed model, 'cooperators' contribute to (and pay for) irrigation management, while 'non-cooperators' refuse to comply with their obligations. The fundamental dynamics of the model arise from the observation that farmers cooperate i) if they feel sure that (sufficient) others will also cooperate, and ii) if the benefits reaped from

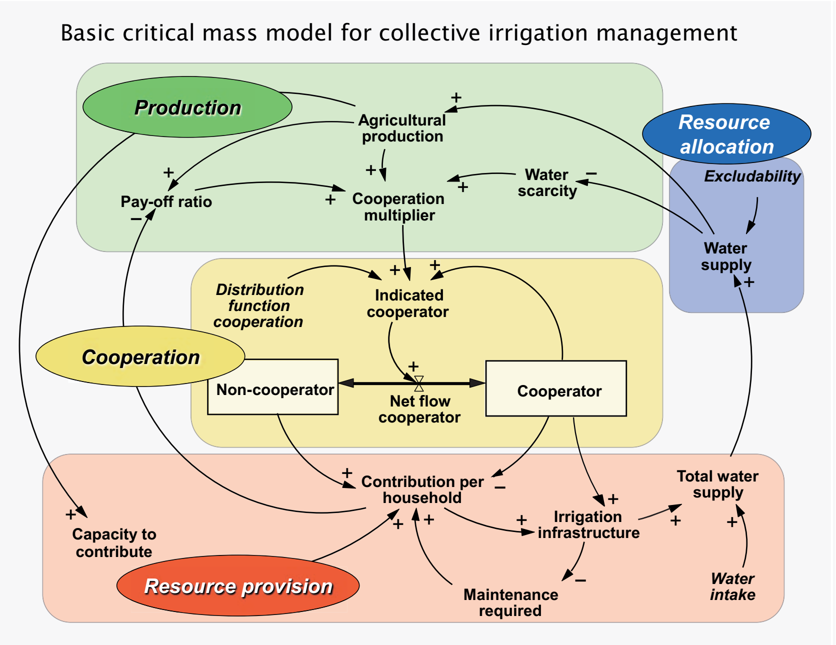

Fig. 1
Fundamental feedback structure of the proposed model for collective irrigation management, building on a general critical mass model of collective action. An arrow denotes a causal relation with a defined link polarity. A positive link polarity (+) indicates that an increase (decrease) of the cause has an increasing (decreasing) result on the effect, while a negative link polarity (–) denotes the opposite situation.

irrigation are large enough. The model also includes the situation of severe water scarcity, in which farmers' willingness to cooperate is increased (Wade 1988; Ostrom 1990).

The model consists of four components: resource provision, cooperation, resource allocation, and production (Figure 1). The current condition of irrigation infrastructure and, as a consequence, water provision depends on the number of cooperators and on the contribution per household, which in turn is determined by required maintenance, the number of cooperators and non-cooperators, as well as households' capacity to contribute. Water supply per household is derived from total water supply and from the influence of the excludability parameter, which denotes the degree to which free-riders can be prevented from receiving water. Hence, water supply per household differs between cooperating and non-cooperating users, and, consequently, so do water scarcity, agricultural production, pay-off, and capacity to contribute.[5] The effects of water scarcity, agricultural production, and pay-off ratio on farmers' choice to cooperate are provided by non-linear multiplier functions, which are combined into a variable termed "cooperation multiplier". This multiplier, together with the current number of cooperators, determines whether the number of cooperating farmers in the next time step will increase or decrease. Agricultural production, finally, affects farmers' capacity to contribute.

The base run of the model corresponds to unsuccessful cooperation and declining irrigation infrastructure. As a consequence, the number of cooperators (total cooperator ratio) decreases (Figure 2, left). Model analysis reveals the conditions under which successful cooperation may arise, for example if initial cooperation is (slightly) higher than in the base run (Figure 2, right). This sensitivity analysis includes parameter variation as well as variation of functional relations, in particular of the (non-linear) multiplier functions conveying the effect of a change of the influencing factors on farmers' decisions to cooperate or not to cooperate.

Limitations of the proposed dynamic model relate to two different levels: they consist, first, in model-specific shortcomings, and second, in restricted transferability to other contexts. While the first limitation can be overcome by means of appropriate extensions to the suggested model, for example by distinguishing households with different income generation patterns (Gallati 2008a, 2008b), the second touches upon a more fundamental aspect. The proposed model can be transferred to other contexts *only* if the dynamics of cooperation can be appropriately described by means of a theory of collective action. Consequently, the proposed model can be used for comparative studies, and hence contribute to overcoming the 'ideographic trap', only if the dynamics of cooperation rely on similar mechanisms.[6] For situations in which these conditions are fulfilled, a system dynamics model can be considered a consistent, testable theory of the observed phenomena.

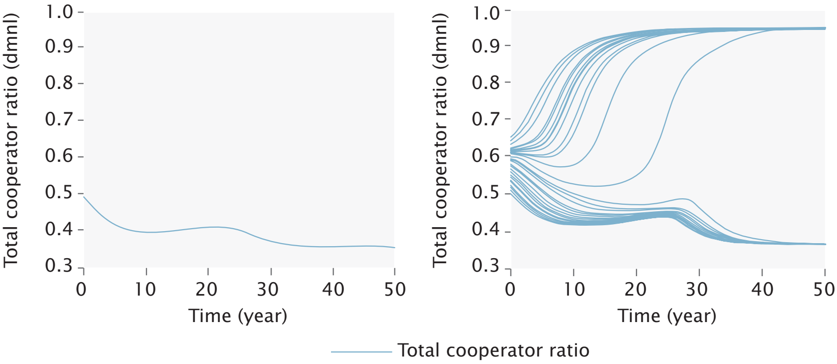

Fig. 2
Left: Decline of cooperation (total cooperator ratio) and reaching of the lower equilibrium of unsuccessful cooperation. Right: Slightly higher initial cooperation may result in successful cooperation.

We stated that system dynamics is an adequate method to deal with complex dynamic problems in a way that provides generalisable insights while including stakeholders' knowledge and perspectives. The case study presented above indicates that in order to comply with this double claim, the research project should combine participatory elements with (theory-based) modelling in an iterative process, with a view to testing underpinning causal relations and in order to enable participatory generation of confidence in the model. Moreover, interaction with stakeholders was indispensable to clarify the model focus and to establish the relative importance of different influencing factors, while grounding in theory provided a robust framework to capture the dynamic structure of the problem. These observations are corroborated by general findings with regard to computer-based models for policy-making advanced by Förster and colleagues (2003).

17.6 Conclusions

We have shown that system dynamics complies to a large extent with the requirements of transdisciplinary research, and that, consequently, system dynamics can provide a valuable research and integration method for sustainability research. Moreover, we hope to have demonstrated that this approach may provide genuine contributions to research for sustainable development, in particular with regard to overcoming the 'ideographic' and 'theory' traps. By means of a case study we have shown both the potentials and the limitations of a system dynamics approach as a method in research for sustainable development, emphasising the necessity of carefully investigating the conditions under which a specific model can be transferred from one context to another. We conclude that system dynamics could be involved more frequently in transdisciplinary research, especially for the analysis and solution of complex dynamic problems. Potentials and limitations of system dynamics with regard to transdisciplinary research for sustainable development should be systematically elucidated, particularly in comparison to, and in combination with, other (modelling) methods. Process design with regard to linking stakeholder participation with (theory-based) modelling deserves particular attention.

Endnotes

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[3] It is clear that the dynamics of a system can also be appropriately described and analysed using a logic different from causality, especially in contexts where indigenous knowledge contributes to the understanding of the system in a transdisciplinary research process (Rist and Dahdouh-Guebas 2006). Indeed, indigenous knowledge is often based on epistemological premises that differ radically from those upon which Western scientific thinking is usually based (ibid.). In such contexts, the use of system dynamics modelling as a tool for a transdisciplinary research approach is not precluded, on the contrary: like other tools which fulfil the epistemic requirements of transdisciplinary research for sustainable development, it can help both the researchers committed to Western scientific paradigms as well as the other stakeholders involved in the process of knowledge co-production to jointly develop valuable insights. Care must be given, however, to take into account the inherent tendency of researchers to subsume other epistemologies under Western causality, unwittingly leading to a form of epistemological hegemony (Pohl et al 2010).

[4] According to Lane and Smart (1996) three lines of thinking with regard to the concept of generic models can be identified in system dynamics: canonical situation models, abstracted microstructures, and counter-intuitive system archetypes. In the present article, ‘generic model’ refers to a canonical situation model, describing the generalisation and simplification of case study models with the aim of representing a wider class of situations.

[5] This differentiation, however, is not included in Figure 1, in order to keep the figure more transparent.

[6] Interviews with farmers in Saz, Kyrgyzstan, and in the Burguret river catchment in Laikipia District, Kenya, revealed significant differences with regard to water supply and influencing factors affecting farmers’ behaviour. The results indicated that, in the Burguret case, social interactions among farmers played a minor role, while economic considerations and sanctions were predominant. As a result, the model developed for Kyrgyzstan was not applied to the situation in Burguret (Gallati 2008a).

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