Dissertation

Modelling system innovations in coupled human-technology-environment systems

Georg Holtz

Institute of Environmental Systems Research
Department of Mathematics / Computer Science
University of Osnabrück
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Supervised by:

Prof. Dr. Claudia Pahl-Wostl, Institute of Environmental Systems Research, University of Osnabrück, Germany

PD Dr. Bernhard Truffer, Department Innovation Research in Utility Sectors, Eawag Dübendorf, Switzerland

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Summary

Achieving sustainability requires major changes in several areas in which society makes use of technology to meet human needs and while doing so influences the environment, such as agriculture, mobility, power production and water management. The awareness of a need for radical changes is accompanied by an increasing recognition of the interconnectedness of technological, socio-cultural and environmental elements and processes. This has led to an increasing amount of research on system innovations. System innovations refer to changes to a "structurally different" system involving radical changes in the technological and socio-cultural domains and are often contrasted to incremental (technological) change. System innovations involve many actors and many factors, and developments at multiple levels interact. Control over such processes is distributed, they are laden with uncertainty and they exhibit sometimes surprising and unexpected behaviour due to non-linear dynamics and emergent properties involved.

Our current understanding of system innovations is limited and the need for an enhanced understanding has clearly been recognized. Computer simulation models seem a promising tool to that end as they already proved to be useful to enhance the understanding of complex systems in many fields like complex chemistry, ecosystems and physics. However, system innovations are mostly processes in social systems. In the social sciences, the application of formal simulation models has a far shorter history and the availability of formalized (and widely accepted) theories and generalizations is low compared to the natural sciences. It is thus not clear-cut which role computer simulation models can play with respect to system innovations. This thesis fathoms the potential of computer simulation models for enhancing our understanding of system innovations and takes some first steps towards fruitful application of models.

A theoretical and methodological discussion outlines how models can in principle contribute to an understanding of social macro-processes through facilitating a causal reconstruction of processes that account for the respective observed phenomenon. The view adopted regarding the representation of the social world thereby is that of reciprocity of agency and structure. Compared to the sociological literature the perspective is extended beyond comprising actors and institutions but encompasses also other entities, especially technological artefacts.

The thesis then relates the current state of empirical and conceptual work in the field of transition[1] research to insights from modelling of complex systems. The intrinsic characteristics of system innovations and the knowledge base available to study them are explicated and implicated challenges and opportunities for model application are discussed. This is complemented by a review of the few existing models of system innovations.

[1] The terms "transition" and "system innovation" are used interchangeably.

The thesis further develops a specification of the regime concept. A regime refers to a dominant structure which originates incremental change but resists system innovations. The concept of "regime" is at the heart of the multi-level perspective, the most widely used framework of transition research, but it is yet only loosely defined. The absence of shared definitions, concept specifications and operationalizations of key concepts of transition research is a major obstacle for defining (and especially for comparing) models. In this thesis, five defining characteristics of regimes are developed and a method to structure and graphically represent knowledge about a regime is introduced.

Furthermore, theoretical and conceptual work has been complemented by hands-on experience to make methodological and theoretical deliberations tangible. An agent-based model has been developed which addresses the transition from rainfed to irrigated agriculture in the Upper Guadiana, Spain. The purpose of the model is to bridge a gap in the explanation for the observed process. Case specific literature provides information on driving forces (technological development, changes in regulations) and consequences (amount of irrigation). The model focuses on the farmers which "translate" driving forces into practices of irrigation and water use. It studies the effect of weights farmers attach to a list of priorities. The main findings are that interactions of factors have to be considered and that it is important to acknowledge heterogeneity of farm types to understand empirically observed land-use changes.

Based on the outlined work, different possibilities to model system innovations have been abstracted and discussed with respect to their advantages and limitations: a) functional subsystems, b) interacting structures (niches, regimes and landscape) as suggested by the multi-level perspective and c) micro-level entities (actors, technological artefacts, institutions, etc.). None of these representations is superior to the other ones per se but each features certain advantages and drawbacks. The model purpose is a necessary guideline to choose an appropriate representation and to distinguish those parts and aspects of a system which need to be captured from negligible ones.

The main findings of this thesis can be summarized as follows: System innovations feature several characteristics which put model-based approaches to this topic on the most challenging edge of the broader endeavour of understanding and modelling social systems. Those are the significance of emergent decay and re-creation of structure during system innovations; the vast scope of system innovations involving several types of subsystems (consumption, production, governance, and nature); the intertwinement of system innovations with their governance – a field which is hardly accessible to modelling; the complexity of the topic; and the unpredictability of innovations.

Still, it is concluded that models can be useful as thinking tools. In any case, given the complexity of the topic and the underdeveloped knowledge base, adhering to transparency is essential. In a field as vast and complex as system innovations this requires either very strong simplifications or restricting a model's scope to some parts or aspects of an overall process. This thesis proposes to make use of existing building blocks of understanding of an intermediate level of complexity – e.g. timing and kind of multi-level interactions - to define abstractions and model scope. The challenge to identify, specify, understand and relate conceptual building blocks, to identify the contexts and situations in which each of them becomes relevant and to explicate their role in the overall system innovation could be an agenda for transition modelling for the coming years.

Modelling system innovations will remain a huge challenge in the near future. However, this thesis fathoms that models can be valuable tools contributing to the enhancement of the knowledge base of the field; little by little adding to answers of the "big questions". The specific role(s) models of system innovations can play in this endeavour needs to be further explored and discussed.

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Chapter 1: Introduction

1.1 A need for system innovations

Achieving sustainability requires major changes in several areas in which society makes use of technology to meet human needs and while doing so influences the environment, such as agriculture, mobility, power production and water management (UNEP 2007; IPCC 2007; Stern, Peters et al. 2006). For example, 20th century water management was based on the construction of massive infrastructure and an engineering "predict & control" paradigm and brought tremendous benefits. However, important problems remain unresolved, for example more than one billion people worldwide lack access to safe drinking water (Gleick 2003). Other, new challenges for water-management arise from changing frequency and amount of precipitation rooted in climate change (Bates, Kundzewicz et al. 2008) and from demographic changes and consumption patterns, e.g. rapid industrialization and urbanisation in the developing world (UNFPA 2003). Those new developments are characterised by a high level of uncertainty and past approaches relying on infrastructure with life-times of several decades seem too inflexible to deal with them. It must be noted that past approaches induced new problems themselves, especially environmental problems like a loss of biodiversity (Gleick 2003). Water management needs to undergo some fundamental change in order to meet those challenges (Pahl-Wostl 2007a; UNEP 2007; Figuères, Tortajada et al. 2003). Similar insights are reported regarding other areas like mobility and power production (UNEP 2007; IPCC 2007; Stern, Peters et al. 2006).

This awareness of a need for radical changes is accompanied by an increasing recognition of the interconnectedness of technological, socio-cultural and environmental elements and processes. I will therefore use the notion of coupled human-technology-environment systems (HTE-systems) to refer to systems through which society meets human needs. The interest for radical change in such highly connected systems has led to an increasing amount of research on system innovations (e.g. Vellinga and Herb 1999; KSI; Elzen, Geels et al. 2004; Geels 2005a; Olsthoorn and Wieczorek 2006). System innovations refer to changes to a "structurally different" system involving changes in the technological and socio-cultural domains and are often contrasted to incremental (technological) change – providing enhanced functionality by "doing the same thing but better". An example for a system innovation in water management is the "room for the river" programme in the Netherlands. For a long period of time the dominant paradigm in the Netherlands has been that of controlling water building dikes. Throughout the centuries, space for the rivers has become only more limited and the rivers have been wedged between high dikes, while the level of the land behind the dikes has been dropping. At the same time, the land behind the river embankments has become more heavily used and populated. Nowadays, a flood would have disastrous results. Climate change will likely entail future high river discharges; however, precise forecasts of future discharge levels are frustrated by high levels of uncertainty and therefore incremental change - further increasing dikes - can no longer provide the aspired security. In 2006 the Dutch Cabinet drew up the Spatial Planning Key Decision "Room for the River", which aims to break the past trend of building more and stronger dikes and instead envisages other measures to cope with greater volumes of water in a safe manner while at the same time improving the quality of the environment of the river basin. This includes measures like creation of retention areas and dike displacements which involve spaces which are now populated or otherwise used. Giving room back to water breaks with a deeply entrenched attitude towards water and requires a new way of thinking, a paradigm shift from "controlling water" to "living with water". This agenda further creates new interdependencies between water managers, spatial planners, NGOs and inhabitants involving a change in water management from a hierarchical and technocratic way of working into a more open, deliberative and decentralised way of working (van den Brink 2008).

System innovations like the room for the river programme are envisaged to provide possibilities for large jumps in environmental efficiency. Because of this potential, policy makers, NGOs and large firms are increasingly interested in system innovations (Elzen, Geels et al. 2004; Olsthoorn and Wieczorek 2006). The answers to questions such as "under which conditions do system innovations occur?" and "is it possible to induce and govern system innovations and if so, how?" are of major interest. However, our current understanding of system innovations is limited and the need to better understand system innovations has clearly been recognized (KSI; Elzen, Geels et al. 2004; Elzen and Wieczorek 2005; Olsthoorn and Wieczorek 2006). An understanding of a system and of ongoing change processes is required to assess system behaviour if influenced by some stimulus like e.g. a policy. Computer simulation models are tools which feature some characteristics that make them valuable for understanding complex systems (see chapter 2 and paper 2 in the appendix). Hence they might as well be useful for enhancing our understanding of system innovations in HTE-systems. This thesis fathoms the potential of computer simulation models for doing so and takes some first steps towards fruitful application of models.

1.2 A shared perspective

That system innovations actually constitute an own research field and it is thus meaningful to contemplate on the role of models of system innovations without being more specific – say models of system innovations in water management or models of system innovations in mobility systems - may not be obvious. HTE-systems in different areas surely exhibit idiosyncratic characteristics that should be considered in a detailed analysis. For example, water related infrastructure like dikes has a very long life-time or, to give another example, the role of markets is rather weak in water management and comparably stronger regarding mobility. Such specific characteristics eventually may lead to differences in overall dynamics of system innovations. However, the envisioned changes towards sustainability share some commonalities across different areas which allow a shared perspective and motivate a joint research effort to enhance our understanding of such processes (Vellinga and Herb 1999; Rotmans, Kemp et al. 2001a; KSI; Elzen, Geels et al. 2004). These commonalities comprise the involvement of many actors and many factors and the interaction of developments on multiple levels. Control over system innovations is distributed among the actors involved, while at the same time these actors may not hold similar opinions on whether a problem exists at all, about the nature of the problem and about fruitful approaches to solve the problem. Furthermore, processes are laden with uncertainty and HTE-systems are complex systems involving non-linear dynamics and emergent properties. Consequently they exhibit surprising and unexpected pattern in their dynamics and their structure. System response to some intervention is potentially highly sensitive to the state of the system and to the specificities of the external stimulus and may thus differ considerably from the intended changes. Finally, HTE-systems are often perceived to be resistant to change and to be "locked-in" to a non-sustainable pathway. This resistance to change arises from a range of sources like sunk costs, vested interests and perceptions of "normality" and furthermore from the interdependency of system elements such like technological complementarities, routine utilization of certain technologies in certain situations, emission standards defined based on technological possibilities etc. (see chapter 2.2 and paper 3). The questions of how to "un-lock" such systems and to induce or govern change processes towards sustainability given complexity, uncertainty and distributed control are similar with respect to HTE-systems in different areas. Along these pillars, the field of transition[1] research has developed. Transition researchers investigate long-term fundamental change processes arising from complex (sub-)processes on multiple levels and in various domains (economic, technological, institutional, and socio-cultural). Only recently first attempts have been made to utilize in this field formal methods like computer models and this thesis can be seen as part of this endeavour.

1.3 The contribution of this thesis

Computer models can enhance our understanding of complex systems. This is achieved through representing (assumptions about) elements and interdependencies of the real systems. The specific form of model elements and interdependencies influences the resulting dynamics of the modelled system and determines its emergent properties. In this way computer simulation models mimic the

[1] The terms "transition" and "system innovation" refer to the same type of process. In the introductory chapters and in the synthesis of this thesis I have chosen the term "system innovation" since in my view this conveys better the character of the processes under investigation. Further, "transition" is somewhat more strongly attached to a specific view involving the multi-level and multi-phase frameworks (see chapter 2.2). However, in the articles outlined in chapter 4 the term "transition" is used since this has become the somewhat dominant term in the literature.

properties and dynamics of real complex systems and in doing so can help to draw conclusions on the relation of system structure and corresponding dynamics and emergent properties. Hence, they provide a valuable means to generate insights about general patterns in system behaviour and can be used to investigate and explore alternative scenarios, as well as elucidate ways in which a system can be intervened or managed. Computer simulation models proved to be useful tools to enhance the understanding of complex topics like e.g. ecosystem dynamics (Pahl-Wostl 1995; Gunderson and Holling 2002). It is thus justifiable to assume that computer models may also be helpful tools to understand system innovations. However, system innovations are mostly processes in social systems. In the social sciences, the application of formal simulation models has a far shorter history than the modelling of physical and ecological systems and this approach has not yet arrived in the main stream of the social sciences (or is just about to do so; Gilbert and Troitzsch 1999; Axelrod 2003). This limited application of simulation models is in line with a low availability of formalized (and widely accepted) theories and generalizations in the social sciences, compared to the natural sciences. This is rooted in several characteristics of social systems hindering generalizations and the application of formal models, most notably the heterogeneity, flexibility and adaptability of human behaviour, the role of institutions[2] and the contingency of processes in social systems (Little 1993; Mayntz 2002, 2009; Flyvbjerg 2001). How to deal with these difficulties is though debated as well as whether generalization and theorizing is a useful approach in the social sciences at all (cf. Little 1993; Flyvbjerg 2001; Mayntz 2002; Hedström 2008). It is thus not clear-cut which role computer simulation models can play with respect to an understanding of system innovations. The first research question of this thesis is therefore:

RQ 1: What can computer simulation models contribute to an understanding of system innovations in coupled human-technology-environment systems?

The answer to this question is dependent on the availability of formalized representations of system innovations (or the possibility to develop such), on their transferability into computer models and on the characteristics of resulting computer simulations models (e.g. the role of stochastic effects). The second research question is interwoven with the first one:

RQ 2: Does the topic of system innovations pose specific challenges to model development?

These first two research questions focus on methodological considerations dealing especially with the purpose of modelling and simulation, the feasible scope of models and fruitful ways of using computer simulation models. In order to actually develop models, it further needs to be clarified what are the constituents of a model of a system innovation in a HTE-system. The vast scope of HTE-systems requires an integrated perspective transcending disciplinary limits and there is no

[2] Throughout this thesis institutions are understood as formal and informal rules of the game such as for example, laws, contracts, social norms, role patterns, routines.

obvious or even established way of defining elements and interactions of the systems involved. Research question three is therefore:

RQ 3: How to represent coupled human-technology-environment systems in models?

These questions are approached as follows: chapter 2 outlines the conceptual background. It discusses how macro-level developments like system innovations can in principle be understood through interactions of a micro- and a macro-level (Coleman 1990) and why especially the inference of macro-dynamics from underlying micro-behaviour is problematic in complex social systems. It is then argued that computer models are in principle useful tools to analyse this latter micro-macro-link. Further, an introduction to the field of transition research provides an overview of the kind of process investigated here and introduces main assumptions and some basic concepts to which is referred in later chapters. Chapter 3 discusses the methods applied in this thesis, namely literature research and (agent-based) modelling. The main work done during this thesis has been organized in four research articles. Chapter 4 gives an overview of the contents of these papers. The papers in full length are either published as specified in chapter 4 or appended to this main text. Paper 1 "Challenges and Opportunities for transition modelling" (abbreviated as "challenges and opportunities" from here on) relates the current state of empirical and conceptual work on system innovations to insights from modelling of complex systems and draws conclusions on model development and application. Paper 2 "Transition modelling – current state and future routes" (abbreviated as "current state") discusses to which extent and in which way a model can simplify the real process. A review of recent models is complemented by a conceptual discussion which adds some insights to those gained in paper 1. Paper 3 "Specifying ‘Regime’ - A Framework for Defining and Describing Regimes in Transition Research" ("specifying regime" from here on), investigates the concept of regime. A regime refers to a dominant coherent configuration of entities which originates incremental change but resists system innovations. This concept is at the heart of the multi-level perspective, the most widely used framework of transition research (see chapter 2.2). In order to guide processes of regime identification, the paper develops five defining characteristics of regimes. Further a method useful to structure and graphically represent knowledge about a regime is introduced. Paper 4 "Using an agent-based model to analyse the role of farmers’ characteristics for land-use change in an agricultural system and for related groundwater over-exploitation" ("Guadiana model paper" from here on) reports on a model of the transition from rainfed to irrigated agriculture in the Upper Guadiana Basin, Spain. This hands-on experience complemented theoretical and conceptual work and made methodological and theoretical deliberations tangible. The results derived in these articles with respect to the research questions posed are synthesised in chapter 5 and furthermore future research opportunities are outlined. Finally chapter 6 presents the conclusions.

Chapter 2: Conceptual background

2.1 Computer simulation models as tools for understanding developments in coupled human-technology-environment systems

RQ 1 refers to understanding system innovations. Broadly speaking, something is understood, when we have an explanation that answers the "why"-question. This chapter elaborates somewhat more on the way an "explanation" is understood in this thesis and on how computer simulation models can in principle aid to develop such an explanation.

The natural sciences explain some observed phenomenon through formulating natural laws which are universally applicable and which can be parameterized using case-specific data to obtain answers on that specific case. For example, Newton's $F = m \cdot a$ applies to all kinds of bodies everywhere in the Universe[3]. Since there is a high level of consent on this view on explanation within the natural sciences and furthermore the representation of natural and environmental systems plays a minor role in this thesis, what constitutes an explanation in natural and environmental systems will not be further treated here.

In the social sciences what actually constitutes an "explanation" is not so clear-cut (cf. the discussion on different kinds of explanation in Hedström 2008). The mode of explanation followed in this thesis explains some phenomenon through causal reconstruction of processes that account for the observed phenomenon (Coleman 1990; Mayntz 2004, 2009; Hedström 2008). That typically involves causal regression to elements on a lower level of abstraction. Figure 1 shows how dynamics on a level of interest (the macro-level) are understood in the mode of explanation adopted here through causal reconstruction involving a lower level of abstraction (the micro-level).

An illustrative example: Schelling's model of segregation

In order to illustrate the various relations between macro- and micro-level in the "Coleman-boat" (figure 1) I will refer to Schelling's famous model of segregation (Schelling 1969). In this model, two groups of actors live on a grid. Each actor is satisfied with his current location, if at least *x %* of his neighbours belong to his own group. If this is not the case, the actor moves to a random other grid cell. When running the model, one observes the emergence of clusters of similar agents on the

[3] Within the limits of the Newtonian mechanics, i.e. not going to very small scales (quantum mechanics are required in this realm) or very high speeds (the realm of relativity theory).

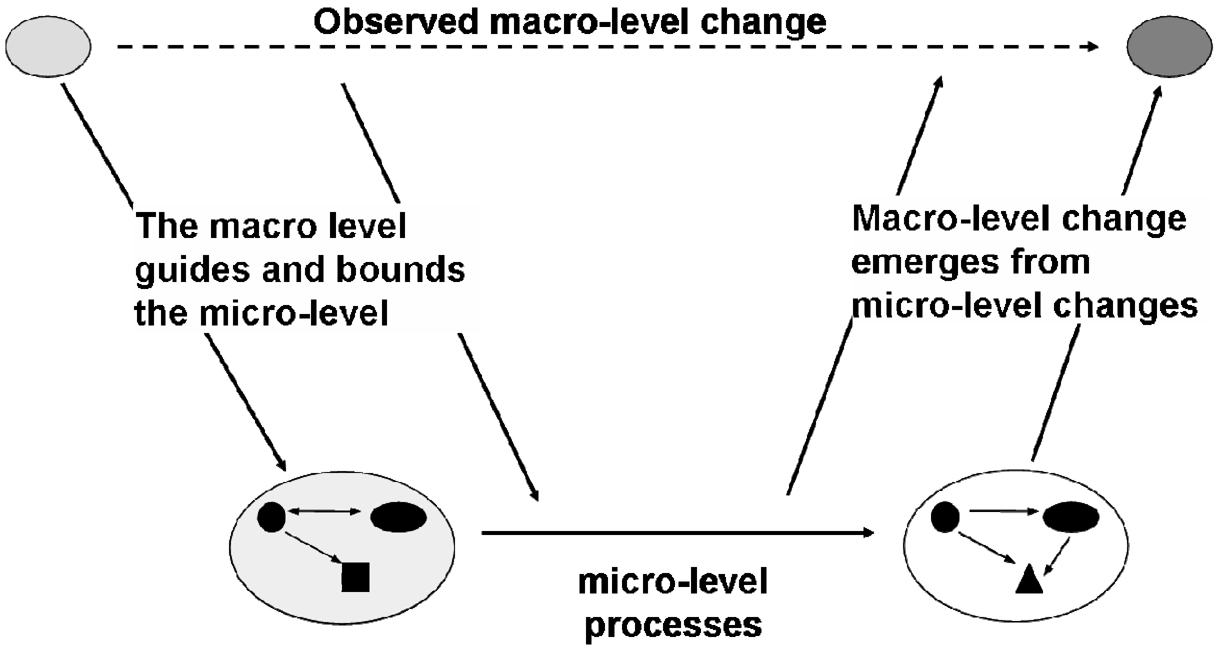

Figure 1: Interactions between micro- and macro-level in generating observable macro-level change (based on Coleman 1990).

grid as shown in figure 2. The main message of this model is that although individual actors may be quite tolerant (e.g. *x=30*, i.e. up to *70%* of an actors neighbours may belong to the other group before the actor leaves his current location), the groups are rather segregated in the overall emerging situation (with *x=30*, in average each actor has around *70%* of neighbours belonging to his own group when the model reaches a stable state). Hence, the system features emergent properties which can not directly be derived from the individual actors' characteristics.

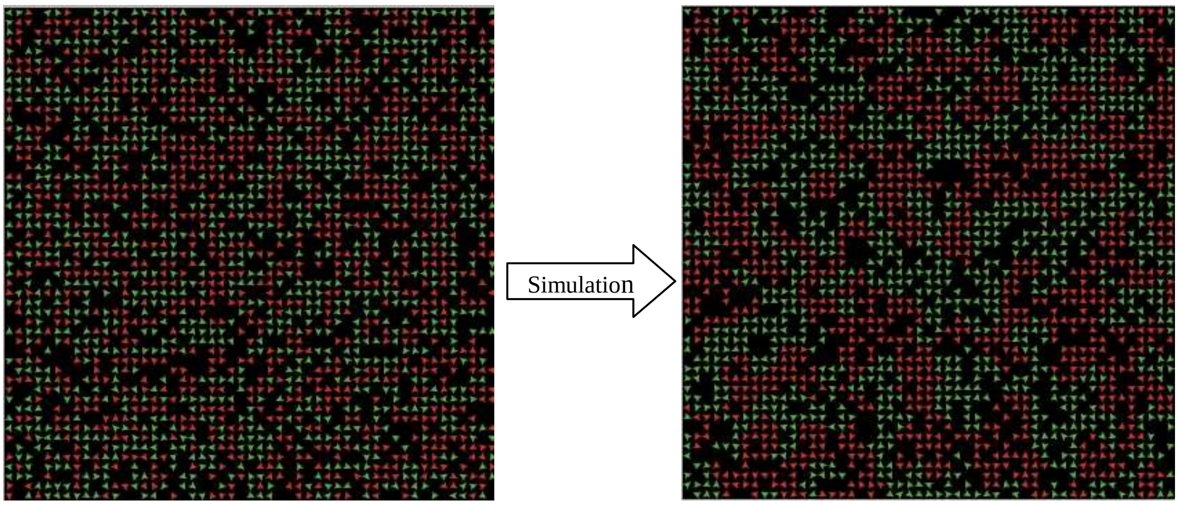

Figure 2: Schellings' model of segregation. Two groups exist (green and red) which form clusters of similar actors during the course of a simulation run (see text for an explanation of the model). The figure was created using Netlogo 3.1.4 (http://ccl.northwestern.edu/netlogo/).

Schelling’s model is an example that includes three relations between micro- and macro- level: the macro-level is constituted through a specific micro-level situation, namely the location of actors on the grid, and analysed in terms of a macro-structure, the corresponding level of segregation. Processes on the micro-level drive the dynamics. Actors move around when they are unsatisfied with their current location. The observed change on the macro-level can be finally explained as unintended, emergent consequence of the interactions of many individual actors on the micro-level. The main mechanism behind the observed segregation is that clusters form around stable nuclei of similar actors which finally results in actors in the inner part of these clusters having 100% of neighbours belonging to their own group.

In this model, the macro level is decisive for the overall dynamics (only) through defining the location of individual actors and thus specifying the neighbourhood of each actor. In other cases, the macro-level may not only have influence through specifying the local options, incentives and constraints actors are facing on the micro-level, but the overall macro-level situation itself may also have direct influence. The reason is that actors may be able to perceive their system and may be able to reflect and adapt their behaviour. This perception of the system then includes the micro-level, say behaviour of selected other actors, but can also include emergent properties on the macro level (e.g. coalitions, mass behaviour, environmental impacts, market shares, etc.). This perception of the macro situation then may influence the actors’ actions. Gilbert (2002) has proposed an extension of the Schelling model that incorporates this effect. In extension to the basic model, actors’ evaluation of a grid cell depends also on the history of this cell. A cell can be labelled as being a good or bad place to live for someone of a specific group, which is in turn dependent on the history of this grid cell. So the historical developments on the macro-level are decisive for understanding actual micro-level processes. In this way, through actors who perceive emergent properties on the macro-level and adjust their behaviour correspondingly, the macro-level has a direct feedback to the micro-level (this is sometimes called second-order emergence; Gilbert 2002; Squazzoni 2008a). Broadly speaking, this can result in self-reinforcing processes like the bandwagon effect but can also stabilize certain systems states, e.g. if shared norms restrict individual behaviour (Squazzoni 2008a).

The micro-level

In cases which are more complex than Schelling’s model, it is not easily definable what constitutes an appropriate micro-level for explaining a macro-phenomenon of interest. One benchmark is that the level of individuals may be considered a lower bound for regressions to lower levels being meaningful for studying social phenomena. Beyond that, Coleman (1990) pragmatically suggests that an explanation is sufficiently fundamental when it provides a basis for knowledgeable intervention which can change system behaviour. I suggest phrasing that a bit more general: an explanation should facilitate answering some "what if"-question(s) of interest. This extends Coleman's criterion to include also thought experiments about changes which can not directly be implemented as intervention (e.g. "what if environmental awareness increases"). Such thought experiments can for example be of interest to assess the impact of deep cultural trends on the future development of a system of interest.

In any case, a regression to a lower level requires opening the black-box of the system whose dynamics or properties are to be explained and to describe it in terms of system elements and interactions. Regarding the required analytical description of social systems, different schools in the social sciences offer different approaches, ranging from those stressing more the systemic character (Luhmann 2008) to those focussing on individual actors (Heath 2005). The view adopted here is that of reciprocity of agency and structure (Giddens 1984; Little 1993; Mayntz 2002; Hedström 2008). Actors' activities are influenced through the (social) structure since the structure (e.g. norms, network constellations) provides options, incentives and constraints. Actors are thereby seen as being influenced by the structure but their actions are not completely determined by that structure, i.e. there is room for agency. The structure in turn is maintained through continuous activities of actors.

The sociological literature referred to here, in whose context Coleman presents his "Coleman boat", mainly focuses on actors and institutions. When transferred to HTE- systems, the idea of explanation through regression to a lower level can be extended to encompass also other entities, especially technological artefacts. The micro-level thus may comprise actors, institutions and various types of other "elements" like technological artefacts and infrastructure. I will use the term "entities" to refer to all those things on the micro-level (cf. Hedström 2008; Mayntz 2004, 2009). HTE-systems feature according macro-structures involving other entities besides actors and institutions. Those are for example the routine utilisation of specific technological artefacts for specific tasks, complementarities and other types of interdependencies between technological artefacts and infrastructure, co-evolution of technological performance and consumers' respective expectations, regulations and standards based on best practices, and cognitive routines of engineers channelling technological development. As social macro-structures may influence the micro-level, this is also true for structures involving other entities. For example, when purchasing a new car, the available infrastructure (fuel stations, repair shops) will influence consumers' decisions among say a petrol-car and a hydrogen-car.

It may sometimes be useful to develop some (preliminary) explanation involving only structures to decompose a macro-level phenomenon. As will be elaborated in chapter 2.2, system innovations are often described in terms of interacting macro-structures (regimes, niches). This may be a useful step, but it does not provide an explanation of system innovations in the sense of providing a basis for "knowledgeable intervention", to use Coleman's criterion, or to answer "what-if" questions. The reason is that macro-dynamics and structures do not directly act and interact but only via influencing actors and their actions. Actors are the driving force in social systems, generating dynamics and reproducing structures. An explanation needs to comprehend how some change in the system alters actors' activities. This requires incorporating some actor model explaining the link between the change in the system and actors' adaptation of activities. In this thesis I therefore understand an explanation of a macro-phenomenon as complete if it incorporates actors and explains the phenomenon as (emergent) outcome of actors' actions in the respective structural context guiding and bounding their actions. Actors may thereby be individuals, but can also be more aggregated actors like firms and organizations whose internal coherence allows ascribing them intentional behaviour. This emphasis of actors is not meant to downplay the role of institutions and other entities on the micro-level - see the adoption of a view of reciprocity of agency and structure above – but to clarify my view on what constitutes a complete explanation of system innovations (see also chapter 2.3).

The micro-macro-link[4]

Using a "Coleman boat"- approach, the major challenge for understanding observed macro-level changes resides in understanding how micro-level processes interact in producing observed macro-level change as emergent outcome, the micro-macro link (Coleman 1990; Hedström 2008). Although the social sciences are far from having developed a unified view on explaining actors behaviour in specific circumstances (i.e. the macro-micro and micro-micro links), at least quite a range of explanatory approaches are available, e.g. the model of the rational actor, norm-driven behaviour, routines, bounded rationality (e.g. Gigerenzer and Selten 2001), socio-psychological models (e.g. Ajzen and Fishbein 1980), belief-desire-opportunity theory (Hedström 2008) etc. In contrast to that, quite few is known on how specific micro-level constellations give rise to specific macro-level properties and dynamics. The reason is that social systems are complex systems involving non-linear interdependencies and dynamics. Non-linear interdependencies do not allow for simple aggregation of individual behaviour or properties and consequently macro-level properties can not easily be deduced from knowledge on the properties of a system's parts. Instead, macro-properties emerge from the interactions of entities on the micro-level. Schellings' model clearly illustrates this. This emergence of macro-phenomena constitutes a serious challenge for research, since directly comprehending emergent outcomes in non-linear dynamic systems exceeds the capacities of humans even in comparably simple cases (Sterman 2000).

Computer simulation models as tools to investigate the micro-macro link

Computer simulation models have proven to be useful for analysing complex systems. They are able to infer emergent behaviour of some model system structure and as such they can be considered useful tools to analyse the micro-macro-link, i.e. the generation of emergent properties

[4] Here and in the following I use micro-macro-*link* to denote the emergence of macro-phenomena from the micro-level (i.e. one direction in the Coleman-boat), while micro-macro-*interactions* is used to refer to the overall concept (i.e. the whole Coleman boat).

and dynamics through processes on the micro-level. The above introduced example of the Schelling model illustrates the challenge of the micro-macro-link and also illustrates that simulations are in principle useful for its analysis. Applying computer simulation models for the analysis of social systems (and social systems coupled to technological and environmental systems) is a rather young approach. In the last two decades, the advent of agent-based models has stimulated a still increasing interest in using such models for the analysis of social systems[5]. Agent-based modelling is introduced in the next chapter 3 and papers 1 ("challenges and opportunities") and 2 ("current state") elaborate more specifically on the application of computer simulation models in the field of transition research which deals with long-term fundamental change in HTE-systems. The potential benefits and opportunities of utilizing computer models are outlined, but also the challenges and limitations involved are discussed. Before going into that discussion, the following first introduces the main assumptions and some basic concepts of the field of transition research which has influenced this thesis to a considerable degree.

2.2 Transition research

The acknowledgement that sustainability of industrialized societies cannot be achieved without fundamental changes in different areas such as mobility and power production has stimulated research aiming at understanding the analytical mechanisms behind change in such systems, as well as of management and policy making issues. Apart from receiving increasing attention in disciplinary fields, research on "transitions" – processes of system innovation – has grown into an own field. Transition research has investigated a diverse set of processes, like for instance the transition from sailing ship to steam ship (Geels 2002), a transition towards a sustainable energy system (Rotmans, Kemp et al. 2001a), a transition in Dutch water management (Van der Brugge, Rotmans et al. 2005), the transformation of utility sectors (Konrad, Truffer et al. 2008), the transition in Swiss food production from industrialized agriculture to sustainable agriculture (Belz 2004), the transition from coal to gas as major energy source in the Netherlands (Correljé and Verbong 2004) and the breakthrough of rock’n roll (Geels 2007). What those processes have in common, and what is thus the unifying perspective of various transition studies, is that those processes can be perceived as coherent long-term change process arising from a complex interplay of processes on multiple levels and in various domains (economic, technological, institutional, socio-cultural) with control over the process being distributed among a diverse set of actors. Proponents of this study area highlight that system innovations have to be studied from a truly interdisciplinary perspective. The innovative contribution of these types of studies is incorporating approaches from different fields like complexity theory, innovation studies, governance studies and

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[5] Agent-based modelling is not the only possible choice (cf. e.g. Yücel and Chiong Meza 2008; Weisbuch, Buskens et al. 2008).

evolutionary economics. Transition researchers have mostly presented qualitative studies utilizing high-level frameworks to structure narrative descriptions (e.g. Elzen, Geels et al. 2004; Geels 2005a; van der Brugge, Rotmans et al. 2005).

The multi-level perspective

It is useful for further discussions in subsequent chapters to briefly introduce some basic concepts of transition research. Most prominent is the multi-level perspective (MLP), a framework nowadays widely used to describe transitions (Rotmans, Kemp et al. 2001a; Geels 2005a, 2005b; Genus and Coles 2008). In this framework, three different levels are identified (see figure 3): the landscape, the regime and niches[6]. The regime denotes those structures whose fundamental change or replacement is to be analysed in the respective study. No dominant definition of "regime" currently exists. Paper 3 ("specifying regime") defines a regime as follows (p. 629):

*A **regime** comprises a coherent configuration of technological, institutional, economic, social, cognitive and physical elements and actors with individual goals, values and beliefs. A regime relates to one or several particular societal functions bearing on basic human needs. The expression, shaping and meeting of needs is an emergent feature of the interaction of many actors in the regime. The specific form of the regime is dynamically stable and not prescribed by external constraints but mainly shaped and maintained through the mutual adaptation and co-evolution of its actors and elements.*

In the most prominent empirical example described in the literature, the transition from sailing ship to steam ship (Geels 2002), the sailing ship regime around 1780 comprised sailing ships with large cargo-holding capacities whose design was encouraged by guaranteed prices and government regulations, two types of ship-owners, namely chartered companies and captain ship owners, a dependency on wind and currents, mail as crucial means for communication and so on.

"Niches" constitute alternatives to the regime. According to Geels and Schot (2007), niches and regimes are similar kinds of structures but different in size and stability. In niches, actor groups involved are smaller and less stable and also shared rules coordinating actions have not yet stabilized but are "in the making". Hence, niches leave more room for agency while regimes feature a comparably stronger role of structure. Niches often emerge around radical technological innovations in some application domain[7] in which they are not exposed to "normal" market forces.

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[6] Some authors (e.g. Rothmans, Kemp et al. 2001a; Timmermans, de Haan et al. 2008) use the distinction into micro, meso and macro level instead of niche, regime and landscape. However, both sets of concepts are not precisely defined and the difference in terminology indicate only minor substantial differences (if any) what leads to a certain exchangeability. To avoid confusion with the micro-macro-level concept introduced in chapter 2.1 I will use niche-regime-landscape only when referring to the MLP of transition research.

[7] Some authors (e.g. Hoogma et al. 2002 as cited in Markard and Truffer 2008) refer to "niche" as an application domain *in which* some technology is applied and *in which* actors' activities deviate from usual

Two types of application domains providing space for niches can be distinguished (Markard and Truffer 2008): 1) market "anomalities", i.e. particular application contexts or consumer preferences deviating significantly from average and 2) spaces deliberately created by some actors, e.g. in order to assess the potential of an innovation. In the example of the transition from sailing ship to steam ship, niches were the first uses of steam ships for passenger transport on inland waterways and usage of steam ships for mail transport, which was stimulated through mail subsidies.

The "landscape" level represents the encompassing system(s) guiding and bounding regime development. It is a different kind of structure than regimes and niches (Geels and Schot 2007). It comprises static or slow changing factors such as deep cultural trends, climate or the material, technical and physical backdrop that sustains society (e.g. long-living infrastructure). It further incorporates dynamic aspects of the regime environment changing on a faster time-scale, like oil-price changes, a financial crisis or disasters. In the shipping example, the landscape refers to changing context conditions like emigration waves and changing regulations regarding colonial trade. The integration of both, slow and fast dynamics in the landscape can best be understood from the application of the MLP: the landscape level comprises those dynamics influencing lower levels which are in turn on short and medium time-scales independent from what is going on at lower levels. Figure 3 shows the MLP. It extends the classical "vertical" view of niche-regime-landscape by adding some "horizontal" embedding of regimes to account for the fact that regimes are not only influenced by a landscape and through niche developments, but are also linked to other regimes (Konrad, Truffer et al. 2008; Geels 2007).

The MLP is a heuristic device that can be applied to cases on different empirical levels. Smith, Sterling et al. (2005) give the example of energy and power generation to illustrate how the term regime may be used as a short-hand for a series of complex, nested real-world phenomena. A global energy regime can be seen as being organised primarily around the extraction, trade and combustion of fossil fuels. Within this energy regime, the electricity generation regimes of industrialized countries are embedded. Those are dominated by rules and practices related to centralized, large-scale (usually thermal) power-generation technology. Within such an electricity regime, e.g. a nuclear, a coal-based and a regime based on renewable energies might be distinguished. Even within the renewable regime, different regimes may be distinguished around e.g. wind-energy, solar-cells and biomass. Geels and Schot (2007) agree that the MLP may be used on different empirical levels and clarify the relation between empirical and analytical levels stating that *"(t)he analyst should first demarcate the empirical level of the object of analysis, and then operationalize the MLP"* (p. 402). Still, despite of the flexibility of the MLP, not every change process should be studied as system innovation. As a lower bound for such phenomena Geels and

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habits. Hence this usage of the notion equals "niche" with the application domain. I will use "niche" in the sense of Geels and Schot (2007) in which regimes and niches are similar kinds of structures comprising technologies, institutions etc.

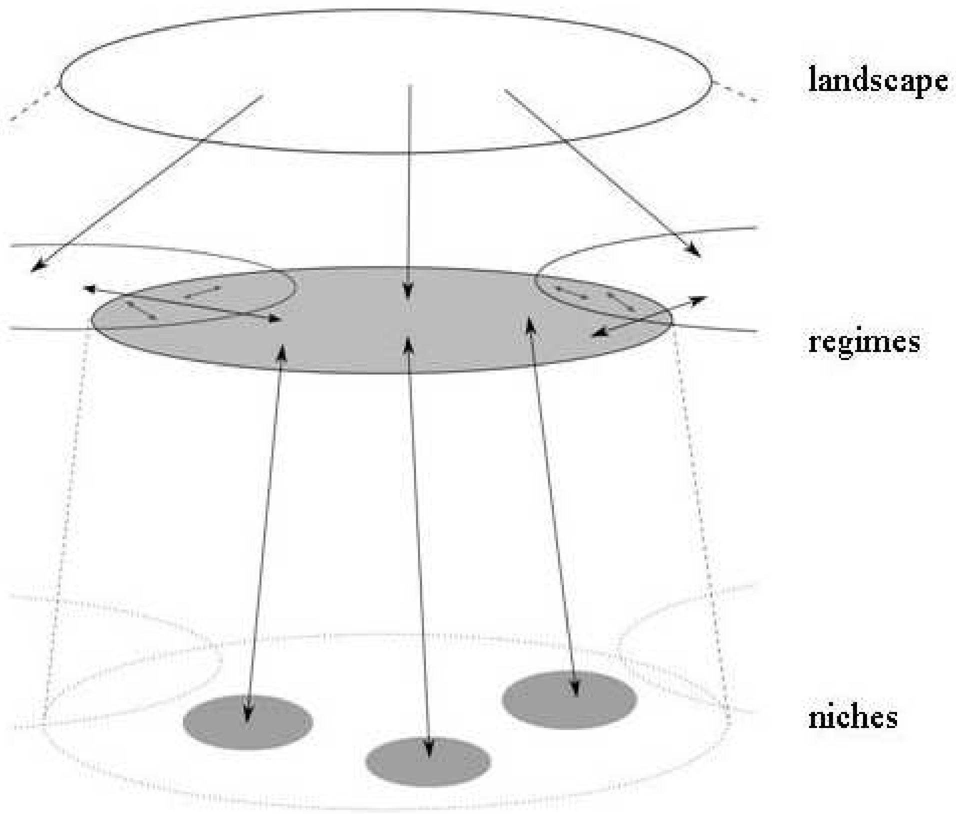

Figure 3: An extended multi-level perspective: the landscape guides and bounds regime development. Niches develop against the backdrop of the incumbent regime and at some point may challenge this regime. Regimes are linked to other regimes through functional relations (e.g. input-output relations, competition for markets or resources) or through structural coupling (joint actors and elements, represented as small arrows in the overlap of regimes).

Schot (2007) contrast system innovations to technological discontinuities arguing that system innovations do not only affect one population (industry) but are more encompassing, affecting also user practices, policies, cultural meaning etc. However, according to Markard and Truffer (2008) many empirical applications of the regime concept have not dealt very carefully with the regime concept in empirical terms and there is no unambiguous regime definition, i.e. the concept can be applied flexibly on different levels and from different perspectives based on the respective research question. Consequently, generalizations from MLP applications need to be derived carefully.

Transition dynamics

The dynamic pattern of a transition is usually depicted as S-formed (see figure 4), associated with four phases (Rotmans, Kemp et al. 2001b): a pre-development phase in which the status quo does not visibly change but things are going on "under the surface", a take-off phase were the process of change gets under way, an acceleration phase were visible changes take place through an accumulation and mutual reinforcement of processes in multiple domains and finally a stabilization phase in which the speed of change decreases and a new dynamic equilibrium is reached. The "classical" pattern of multi-level interactions thereby is as follows: the process starts with a relatively stable regime and alternatives forming niches. Problems within the dominant regime itself or pressure from the landscape level open up the opportunity for niches to challenge the dominant regime. The regime loosens and after a phase of several connected, mutually influencing changes, a new regime emerges, forming a new, stable system. However, it must be noted that other patterns of multi-level interactions have been identified. Two of the most prominent concepts, which will also be referred to in later chapters are briefly presented here. Geels and Schot (2007) identify a typology of four "transition pathways" which are differentiated according to the timing and nature of the interaction between the landscape, regime and niches. According to Geels and Schot transition pathways will differ depending on the state of niche-development when the regime comes under pressure from landscape developments (whether the niche is fully developed or niche innovations are still in an embryonic state) and also the relation between the niche and the regime (competitive or symbiotic) is argued to make a difference. Another typology of transitions is proposed by Smith, Stirling et al. (2005). They distinguish four "transition contexts" spanned by two axes, namely the location of resources necessary to respond to selection pressures (inside or outside the regime) and the level of coordination within the regime.

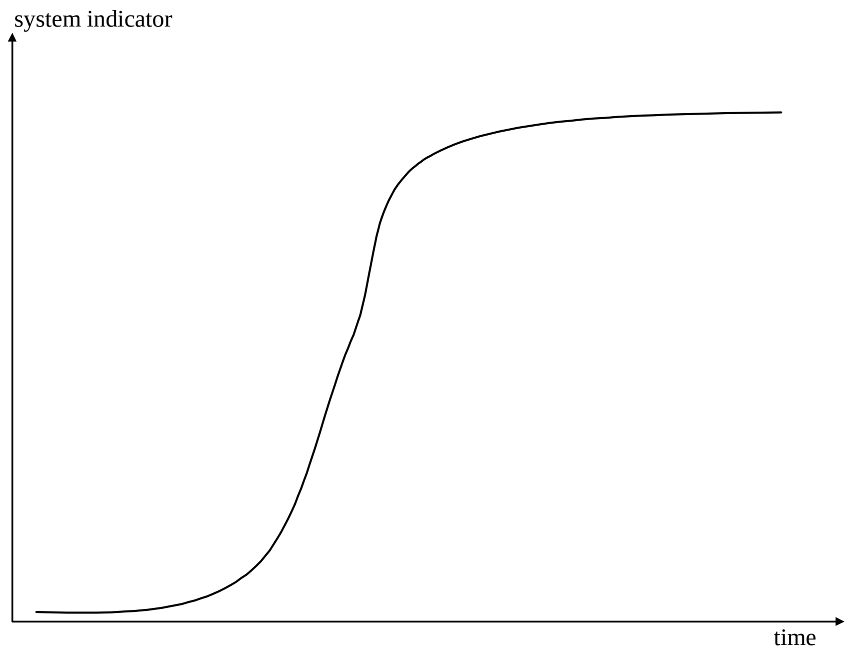

Figure 4: The metaphor of an S-form of system innovations emphasizes the non-linear nature of these processes: slow pre-development, acceleration after take-off and finally saturation.

2.3 The relation between the "Coleman boat" and the multi-level perspective

The previous sub-chapters have introduced two different concepts which involve two respectively three levels, namely the "Coleman boat" describing micro-macro interactions (chapter 2.1) and the multi-level perspective of landscape-regime-niches utilised in transition research (chapter 2.2). This sub-chapter briefly clarifies the relation between these concepts. The micro-macro interactions conceptualized in the Coleman boat refer to the relation between individual entities, most notably actors (micro) and structures arising from entities' interdependencies (macro). The Coleman boat is a stylized illustration how macro structures and the constituting micro-level entities are entwined.

The multi-level perspective (MLP) describes the interactions between three different levels of (macro) structures which differ in size and stability; it does hence not explicitly incorporate micro-level entities. The macro-level structures (primarily the regime and niches) are of interest because they stabilize entities’ activities and interdependencies and channel developments on the micro-level into specific directions. Still, those structures are constituted through interacting entities and an explanation of change in those structures as understood in this thesis (see chapter 2.1) hence requires consideration of the underlying micro-level entities.

A full explanation of a system innovation using the Coleman boat approach and following the structure provided by the MLP would thus comprise the following: a starting point is an explanation of the regime and of niches as emergent structures based on micro-level entities and of their coordination of entities’ dynamics. Then it needs to be explained how developments on the three MLP levels and associated changes of the respective structures - e.g. the regime gets under "pressure", niches "challenge" the regime, the regime "declines", a niche "increases" and its structure "stabilizes" and it eventually becomes the new regime – emerge from and are constituted through (ongoing) changes of micro-level entities’ interactions. When explicating and explaining micro-level processes, it needs to be considered that the respective entities and interactions are influenced in turn through the (changing) macro-level structures.

Chapter 3: Methodology

3.1 Literature review

In order to assess the potential of using computer simulation models to study system innovations, one main methodology applied in this thesis has been literature review. This comprised studying the discussion on the role of theory and generalizations in the social sciences (Little 1993; Mayntz 2000, 2002, 2004, 2009; Flyvbjerg 2001; Hedström 2008). The position taken in this thesis has been outlined above in chapter 2.1.

Further, transition literature has been studied to get an in-depth understanding of the kind of processes to be investigated through model development (e.g. Rotmans, Kemp, et al. 2001a; Elzen, Geels et al. 2004; Geels 2005a, 2005b; Smith, Stirling et al. 2005; Olsthoorn and Wieczorek 2006; Geels and Schot 2007; Markard and Truffer 2008; Konrad, Truffer et al. 2008). Transition literature itself integrates several strands of literatures, e.g. science and technology studies or sociology of technology. An extensive review is given by Geels (2005a). Timmermans, de Haan et al. (2008) provide an overview on how structural change in social systems has been studied from various disciplinary perspectives and Squazzoni (2008b) illustrates how sociologists have theorized on societal transitions. Timmermans, de Haan et al. (2008) conclude that computational and mathematical approaches have been almost absent for studying structural change in social systems. The empirical and conceptual work of transition researchers neither provides formalized concepts directly transferable into computer simulation models with the exception of a small set of computer simulation models labelled as "transition models" which have been published during the time in which this thesis has been accomplished. Those models are reviewed and discussed in paper 2 ("current state"). The review reveals a diversity of approaches in terms of conceptual background and methodology applied as well as diverse and partly contradictory results obtained (see paper 2). The authors are very modest regarding claims about these models' contribution to understanding system innovations. Hence those model exercises do not provide clear answers to the research questions posed in this thesis. Still, the review provided insights regarding possibilities to model system innovations and regarding the challenges involved in doing so.

Given the limited amount of formalized approaches addressing system innovations in their totality, formalized approaches to problem areas which are relevant for system innovations have been studied. The literature on complex (adaptive) systems (e.g. Bak and Chen 1991; Kauffman 1993; Holland 1996; Sterman 2000) provides an understanding of the limitations complex systems pose for understanding them and for analysing and predicting their behaviour. More specifically, the literature on ecosystem dynamics (e.g. Pahl-Wostl 1995; Gunderson and Holling 2002) conveys an understanding of how systems switch between multiple equilibria as a result of interactions of external stimuli and internal processes. The notion of multiple equilibria is central to understanding change in complex systems. The discussion in economics on a "lock-in" to inferior technologies due to increasing returns to adoption (e.g. Arthur 1994) as well as formalized sociological models of mass behaviour (Granovetter 1978) provide some basic insights on mechanisms generating multiple equilibria in social systems. Holling, Gunderson et al. (2002) point out that equilibria need not to be static but the attractor landscape defining equilibria is itself changing as systems evolve. When making this point, they primarily refer to ecosystems and evolutionary time-scales. However due to the high adaptability of humans, in systems incorporating human actors, changes in the attractor landscape happen on time-scales relevant for system innovations (Westley, Carpenter et al. 2002). Sources of change in the attractor landscape of HTE-systems are technological developments, especially radical innovations, and other forms of innovations. For example, an arising environmental awareness attaches additional meaning to usage of technological artefacts (besides e.g. performance and price) and innovative institutions like a CO_2-trading scheme or a CO_2-tax attach costs to CO_2 emissions. The insight that equilibria co-evolve with ongoing processes turns attention towards the generation and spread of innovations. The literature on the diffusion of innovations (e.g. Nakicenovic and Grübler 1991; Rogers 1995) and models thereof (Bass 1969; Valente 1995; Sarkar 1998) inform on drivers and barriers of processes of change that may occur when some innovation enters a system of potential adopters. In those models, the direction of change is fixed; what is of interest is the speed and extent of change. Such models thus do not incorporate the idea of multiple equilibria but are interesting regarding the formalization of self-reinforcing change processes and regarding their insights on effects of system properties like actors' heterogeneity and network structure. Some strands of economics provide formalized models to study the process of innovation development and corresponding economic change and industrial dynamics (e.g. Nelson and Winter 1977; Dosi, Freeman et al. 1988; Freeman 1994; Faber and Frenken 2009). The developed models highlight the role of variation, selection and retention in generating technological innovations and in producing aggregated changes in an economy. In these models change emerges from the interaction of innovation generation and selection of successful firms. These models usually focus on the production sectors and do not cover a similar scope as empirical transition studies including also the user side and governance issues (but see Windrum, Ciarli et al. 2009 for an example explicitly targeting the role of consumers; not considering however co-evolution of production and consumption).

The finding of this literature review concerning the base for models of system innovations can be summarized as follows: the strand of literature targeting system innovations directly is comparably young, uses almost exclusively qualitative concepts and still struggles to precisely define its conceptual basis. It builds on a rich but diverse and mostly unconnected set of literatures, largely from the social sciences. Formal models are available for some aspects related to system innovations, especially models for the economic sector and some models for collective behaviour but are absent for others. Formal models from the field of complexity science which could provide an overarching model paradigm are very abstract and often built with a natural science understanding of complex systems, which is not directly transferable to study social macro-phenomena. Consequently, the adoption of such models for studying system innovations must be done carefully. Open issues identified for developing models of system innovations hence are: operationalization of concepts of transition research; integration of (some of) the existing formal models addressing certain aspects of relevance; developing formal representations for those aspects for which no models exist and making abstract models from the complexity sciences fertile for studying system innovations.

3.2 Model development

As John Holland pointed out: "*Model building is the art of selecting those aspects of a process that are relevant to the question being asked*." (Holland 1996, p. 146). This characterisation of model building as a kind of art refers to the fact that no fixed rules exist for model building but abstraction from reality is (inter alia) guided by intuition and personal taste. The metaphor can be extended to the intertwinement of various aspects that demand consideration. In order to develop an appealing song, harmony, melody, rhythm, dynamics and the choice of instruments must be matched and "fine-tuned". Correspondingly, specification of model objectives, definition of a conceptual model, implementation and validation can not be seen as isolated model development steps but decisions made in one step influence other steps as well and development of a useful model requires matching of the different model steps. Model development requires some sort of tacit knowledge. The other methodology applied in this thesis was therefore hands-on model development. Model development complemented literature research. It provided valuable insights in the challenges that arise when actually developing a model in the realm of system innovations and made methodological and theoretical deliberations tangible.

Agent-based modelling

Paper 4 ("Guadiana model") presents an agent-based model of the transition from rainfed to irrigated agriculture in the Upper Guadiana, Spain. Agent-based models comprise self-contained software parts (the "agents") which interact with each other and their (in silicio) environment (see Weiss 1999 and Ferber 1999 for introductions to agent-based modelling and Gilbert and Troitzsch 1999 for an introduction to simulation in the social sciences). Agent-based modelling is especially suitable to represent social systems since the basic structure of such models – consisting of agents and interactions – mirrors the structure of the social world if described in terms of actors and their interactions. Agent-based modelling allows using the full potential of a computer language to describe agents' characteristics, their perception of their environment, cognitive processes and agents' interactions. It is thus a very flexible method and offers a versatile approach to represent in computer simulations the richness of human behaviour. It is thereby not limited to represent human actors, but other entities like technological artefacts or (parts of) the environment can easily be implemented as (probably passive) agents with which agents representing human actors can interact (e.g. use a technological artefact). This flexibility of the method entails that for designing and implementing an agent-based model many decisions have to be taken; such as specifying how many and which types of agents should be incorporated, choosing one or several models of agent behaviour, defining heterogeneity in attributes and behaviour of agents of the same type and specifying the kind(s) of agent interactions. Due to its flexibility agent-based modelling is applicable to incorporate all kinds of theories from the social sciences. This is an advantage of the method but at the same time burdens the model developer with many often non-trivial decisions.

Given its flexibility it is not surprising that agent-based models show a remarkable bandwidth regarding scales (number of actors represented, spatial, temporal), levels of abstraction chosen, field of application, and complexity of representation. Paper 4 ("Guadiana model") elaborates somewhat more on agent-based modelling, especially on agent-based models of land-use change, the strand of agent-based modelling being closest to the model developed in this thesis.

3.3 Consideration of empirical evidence in models

Chapter 2 has elaborated that simulation models can provide an explanation through identifying a mechanism generating a phenomenon of interest. It has not yet been elaborated in which sense some model output resembles empirical observations of interest, i.e. how model output and the (empirical) phenomenon of interest can be related.

Simulation as a "third way" of doing science

First it should be noted that a model is always an abstraction from reality, ideally capturing the essentials while not including marginal influences. Further, real systems are always open systems prone to many influences which can and should not be captured in every detail in a model. Consequently, a model will not reproduce empirical observations exactly since it (by purpose) neglects certain detail of the real entities and processes in the system and of the context in which the system develops; but a model will (re)produce a stylized version of the phenomenon of interest.

Hence, in modelling exercises both, the model's structure and the model output do not exactly represent reality in all its detail. The purpose is instead to identify a somewhat abstracted model structure which is able to explain a certain abstracted "pattern" of interest in empirical observations. This way of doing science (sometimes called "abduction") is neither inductive nor deductive. Axelrod notes that *"(s)imulation is a third way of doing science. Like deduction, it starts with a set of explicit assumptions. But unlike deduction, it does not prove theorems. Instead, a simulation generates data that can be analyzed inductively. Unlike typical induction, however, the* *simulated data comes from a rigorously specified set of rules rather than direct measurement of the real world. While induction can be used to find patterns in data, and deduction can be used to find consequences of assumptions, simulation modeling can be used as an aid intuition."* (Axelrod 2003, p. 5).

Empirical observations of interest

The empirical observation to be explained by a model is often a "stylized fact". A stylized fact is some perceived generality in empirical observations (Lawson 1989). With respect to system innovations such a stylized fact may be that a system innovation happens if a niche is mature enough to challenge the regime and if the landscape puts pressure on the regime in a way that is helpful for the niche to "take over". This example shows that stylized facts are generalizations but do not need to hold in every single account (e.g. Geels and Schot 2007 identify other transition pathways besides the one mentioned).

Other observations to be explained may be drawn from one case only. For example, the model presented in paper 4 is concerned with explaining the transition from rainfed to irrigated agriculture in the Upper Guadiana, Spain in the time period from 1960 to 2005. In such a case some other criterion than an observed regularity across cases defines the empirical phenomenon of interest. In the Guadiana example this is the sequence of land-uses (and entailed irrigation); the reasoning being that explaining the sequence of land-uses allows answering "what-if" questions of relevance (see chapter 4).

Concept specification and operationalization

The examples illustrate that some observation to be explained may initially not be precise in the sense of referring to measurable empirical entities. Consequently, in order to make model outcome and empirical information comparable, further specification may be required. Schnell, Hill et al. (1999) distinguish two steps. The first step is concept specification: to define the dimensions of a concept. For example "irrigation" in the Guadiana model exercise is specified by the two dimensions "irrigated area" and "amount of water extracted". The second step then is operationalization: defining measurable aspects of the phenomenon of interest - indicators - for each dimension. "Irrigated area" can be measured as hectares while "amount of water extracted" can be measured as m^3/year.

The need for specification and operationalization of concepts raises certain problems for modelling system innovations since for many highly abstract key concepts - most notably "system innovation" itself as well as "regime" and "niche" - no shared definitions exist and (widely accepted) operationalizations are absent. Differences in the chosen concept specification (and operationalization) used in model exercises may lead to model structures which are quite distinct, what raises the problem that conclusions derived from such distinct model structures are hardly comparable. I will briefly illustrate differences in concept specification using the example of "system innovation": sometimes system innovations are specified as "regime change" (e.g. Geels and Schot 2007 and Bergman et al. 2008) what shifts the problem to operationalizing "regime" and to defining when a regime change has happened which is furthermore significantly strong enough to qualify as system innovation and not (only) as incremental change. In other cases single indicators, most often market shares of certain technologies are used to indicate transitions (e.g. Yücel and Chiong Meza 2008). A transition is observed if a certain technology rises from a marginal share to being dominant. A problem with the latter approach is that it is not appropriately capturing the multi-dimensional nature of system innovations expressed in the distinction of system innovations from technological discontinuities made by Geels and Schot (2007) (see chapter 2.2). The absence of (widely accepted) precise definitions and operationalizations of key concepts of transition research leads to a weak knowledge base on which models of system innovations can be based on (see paper 1 "challenges and opportunities" and paper 2 "current state").

Consideration of empirical information in the Guadiana model

In the Guadiana model presented in paper 4, the concept of a "system innovation" is not explicitly used but implicitly specified as land-use change. More specific concepts and operationalizations are then defined with respect to land-use change. The example of irrigation has been outlined above. To give some more examples, the concept of "land-use" has been specified as area (in hectares) of crop-technology combinations. This might seem rather straightforward but it should be noted that this concept specification does for example neglect irrigation schemes (how often and at which hour of the day etc. a farmer irrigates). The dimension crop has been specified and operationalized through the indicators price (€/100kg), yield (100kg/ha/year), costs (€/ha/year), water use (m^3/ha/year) and labour required (AWU/ha/year). These (and other) indicators facilitate comparison of model results to empirical data which is available using the same units. The empirical data was taken from various sources such as the scientific literature, statistical databases (most notably the Eurostat database) and policy plans (see paper 4 "Guadiana model" in the appendix for details of data sources).

Chapter 4: Research articles

The main work of this thesis has been documented in four research articles (see table 1) on which is drawn to answer the research questions posed in this thesis. Paper 3 is published as specified below and the other articles are appended to this main text. This chapter gives an overview of the four articles before the next chapter synthesises the results obtained.

Table 1: Overview of research articles

Paper 1: challenges and opportunities	Holtz, Georg, Joost Vervoort, Emile Chappin and Sharad Karmacharya, "Challenges and Opportunities in Transition Modelling", submitted to the *International Journal of Innovation and Sustainable Development (IJISD),* (submission date: October 5th, 2009)
Paper 2: current state	Holtz, Georg, "Transition modelling – current state and future routes", revised version of an article submitted to *Computational and Mathematical Organization Theory* (date of submission: April, 30th, 2009)
Paper 3: specifying regime	Holtz, Georg, Marcela Brugnach and Claudia Pahl-Wostl, "Specifying 'Regime' - A Framework for Defining and Describing Regimes in Transition Research", *Technological Forecasting & Social Change*: 75 (2008) 623–643. DOI:10.1016/j.techfore.2007.02.010
Paper 4: Guadiana model	Holtz, Georg and Claudia Pahl-Wostl, "Using an agent-based model to analyse the role of farmers' characteristics for land-use change in an agricultural system and for related groundwater over-exploitation", resubmitted to *Environmental Modelling and Software* (date of resubmission of revised version: October 19th, 2009)

4.1 Paper 1: Challenges and opportunities

Paper 1 presents an appraisal of conceptual and methodological issues of studying transitions using computer simulation models. It relates the current state of empirical and conceptual work on transitions to insights from modelling of complex systems. For this, it explicates challenges arising from the intrinsic characteristics of transitions and the knowledge base available to study them:

- An interdisciplinary view comprising institutional, technical, economic, cognitive and social elements is required and a wide range of actors and factors as well as multiple connected levels are involved. These aspects are not, in reality, truly separable when it comes to broad changes. However, the science that has studied them is traditionally divided across disciplines all maintaining different worldviews and basic presumptions.
- Transitions are processes of change in complex systems. Complex systems exhibit surprising and unexpected patterns in their dynamics and their structure which can not be explained from the properties of single system elements nor by a mere aggregation of properties of system's parts. They are irreducible to single elements or their properties.
- Uncertainty is pervasive in transition modelling. Innovations, influences from the system environment and branching points rooted in internal dynamics (e.g. a bandwagon is interrupted or not) induce variability uncertainty. Concrete manifestations are naturally unpredictable ex-ante.
- Different author use slightly varying terminology and propose varying lists of factors or domains incorporated (technology, economics, cultures, routines, infrastructure, rules, institutions, actor groups, networks, environment, paradigm, etc.). The concepts agreed upon up to now by transition researchers (S-Form, multi-level, many actors and factors) are very general and provide little guidance for the evaluation of models. Specification and operationalization of concepts are needed to relate transition models to empirical work and theory.
- Transitions differ from fields in which models proved to be useful tools to enhance understanding and management of complex systems (e.g. physics, weather forecast) in the sense that change in socio-technical systems is at the heart of a transition. When modelling social and socio-technical systems, the fundamental underlying laws are not known (if such laws exist at all in the social sphere). Further, with the exception of economics, existing concepts are rarely elaborated in a formal way easily transferable into a model.

Given the vast scope of transitions, models are suggested as means of communication and collaboration to bridge the conceptual divide between disciplines. Further models have been identified as tools to explore the space of system trajectories created by variability uncertainty. However, the space of simulation results that can be explored in such an exercise is rooted in the structure of the model. A high level of confidence in model structure would be a prerequisite. Due to complexity and epistemic uncertainty the authors do not have such a high level of confidence in the structure of transition models. Addressing challenges arising from complexity and epistemic uncertainty are proposed to be most urgent for transition research and to provide most promising routes for transition modelling.

Still, the vast scope of the topic in combination with its intrinsic complexity and the uncertainty involved constitute severe challenges to model building. Multiple model structures can be argued to be reasonable and a lack of precision of concepts and of empirical work hinders corroboration of the superiority of a specific model structure. Given this, transparency of a model – the ability to comprehend how model outcome and assumptions made are linked **-** is seen as prerequisite that a modelling exercise may contribute to the knowledge base of the modelled system. It is then argued that the objectives of a model exercise play a key role in achieving a transparent and methodologically manageable model and it is concluded that parsimonious models tailored to answer specific questions are the most promising modelling approach.

4.2 Paper 2: Current state

Although modelling system innovations is still in its infancy, some first steps have been made while this thesis was developed. Paper 2 ("current state") reviews the developments of the last few years. Referring to Squazzoni (2008b) it defines a transition model as explaining long-term fundamental change in a societal subsystem[8] as emergent outcome of an underlying generative mechanism. It discusses to which extent and in which way such a generative mechanism can simplify the real process.

In a first step, a brief review of recent transition models reveals substantial differences regarding assumed essential entities and interactions. Major differences relate to what is an appropriate level to define model parts: the entity-level of actors, technologies, institutions, market mechanisms etc. or the more aggregated level of niches and regimes. In a subsequent conceptual discussion it is then argued that the interaction of regime/niche-level (macro) and the entity level (micro) is central to understanding transitions. Transitions are regime changes and this comprises disintegration of an old regime and creation of a new one – they are processes of decay and (re-)creation of structures. Since hitherto models focus either on regimes and niches or on entities they do not address how mutual adaptation of entities leads to integrated "configurations that work" (i.e. niches, regimes) which then eventually compete on a higher level and influence the entities in a way that sustains their existence. Therefore, the reviewed models fall short in capturing arguably essential micro-macro interactions. They further seem strongly simplified in light of the richness of entities and interaction patterns considered in conceptual and empirical work.

[8] In the articles on which this thesis is based I use the notion of a "societal subsystem" which is widely used in transition literature instead of "HTE-system".

It is then argued that increasing the complexity of models is nevertheless not a reasonable way ahead. Building extended, broader models is not advisable given the limited knowledge on the micro-foundation of models and the limited means for validation. This leads to the conclusion that building a transitions model that aims to provide a complete generative mechanism explaining this transition is over-ambitious. Instead, it is recommended to more deliberately making use of building blocks of an intermediate level of complexity – e.g. timing and kind of multi-level interactions – to advance our understanding of transitions. Building blocks constitute a middle ground between the micro-level and overall system innovation dynamics and can help to connect those other levels. Two specific suggestions for modelling exercises are made: 1) Replicating (parts of) empirically analysed historical transitions. This can ultimately lead to improvement of frameworks used for the empirical work. 2) Modelling of general (partial) mechanisms for testing and refining links between some entity constellations and emergent macro-level phenomena. This can help to assess suitability of proposed mechanisms as (partial) explanations of transition dynamics.

4.3 Paper 3: Specifying regime

The absence of shared definitions, concept specifications and operationalizations of key concepts of transition research is a major obstacle for defining (and especially for comparing) transition models. Paper 3 focuses on the concept of "regime" which is at the heart of most empirical studies on system innovations but is yet loosely defined only. The concept "regime" is of central importance for transition research, since it defines the level of societal systems on which system innovations are mainly analyzed. What actually is "the regime" to be researched and possibly managed is however usually not given through clear system boundaries but is a matter of framing and deliberation. In order to guide processes of regime identification, the paper develops five defining characteristics of regimes. They can be summarized as: 1) purpose: regimes relate to a societal function; 2) coherence: regime elements are closely interrelated 3) stability: regimes are dynamically stable 4) non-guidance: they show emergent behaviour and 5) autonomy: they are autonomous in the sense that system development is mostly driven by internal processes. These characteristics are considered to be a minimal but not necessarily exhaustive set of criteria to define regime boundaries. Any system labelled "regime" should match, at least to a certain degree, all these characteristics. However, the actual degree to which the characteristics are exhibited by different regimes will vary. To which degree a regime exhibits the characteristics can partly be influenced while framing the regime; by widening or narrowing the scope of analysis. The characteristics hence facilitate a discussion about traits of various regime framings.

Further a method useful to structure and graphically represent knowledge about a regime is introduced. A regime comprises various actors, having goals, values and beliefs; diverse structural elements like cultural norms, institutions, technologies, infrastructure or ecosystems; and actions executed by the actors influenced by the structural elements and structural elements reproduced and changed by the actions of actors. To structure the knowledge about a regime, actors, elements and actions are grouped in interrelated subsystems. Those subsystems are defined according to "functions" related to the overarching societal function of the regime. E.g. regarding a water-management regime, subsystems could be related to e.g. "provide water", "use water", "clean waste-water" etc. For identifying subsystems it is first proposed to distinguish between social subsystems and natural subsystems of regimes. The dynamics in social subsystems are shaped by human actors, whereas the endogenous dynamics in natural systems are not. This is an important difference as the mechanisms bringing about change, the response to interactions between subsystems and the important variables are fundamentally different. Natural subsystems are viewed as mostly passive resources or sinks. It is further proposed to distinguish "action subsystems" from "intervention subsystems". Action subsystems refer to many similar actors producing products, providing services or using/consuming products. In action subsystems processes of collective behaviour (diffusion of innovations, emergence of norms) are of major interest. Intervention subsystems operate at another level influencing the network of action subsystems. They constitute a regulation level, shaping the institutional and physical context of actors in action subsystems. Power issues and negotiations between actors having partly contrary interest are of major relevance.

Subsystems comprise one or several (types of) actors, a context influencing these actors (institutions, infrastructure etc.) and also actions are considered. Subsystems are linked on the one hand functionally through actions executed in one subsystem influencing another subsystem and on the other hand structurally, through actors or context elements shared between subsystems. This analytical perspective is considered to provide a base to analyse the basic structure and processes characterizing a regime. It is suggested that it helps to understand how a regime "works", to explain emergent properties, to assess future developments, to identify drivers or barriers for change, and to find points for interventions.

4.4 Paper 4: Guadiana model

The context

Paper 4 (Guadiana model) reports on the hands-on modelling exercise that has been conducted during the accomplishment of this thesis and which has complemented conceptual and theoretical work. The model developed addresses the transition from rainfed to irrigated agriculture in the Upper Guadiana, Spain. This model is presented at length in paper 4 which is oriented towards presenting the model and the simulation results. The following complements this through giving more information about the context of the modelling exercise. It provides a somewhat more detailed introduction to the case and briefly discusses why this case is considered interesting from a system innovations point of view.

The Upper Guadiana Basin (UGB) is a rural area located in the Autonomous Region Castilla La Mancha in central Spain (see figure 5). Irrigation of farm land accounts for approximately 90% of total groundwater use. During the last decades, the amount of irrigated farming has increased in the Mancha Occidental aquifer (MOA), the areas main aquifer, and farming practices have changed towards water-intensive crops. This development has lead to an over-exploitation of groundwater resources and has endangered wetlands of high ecological value, Las Tablas de Damiel National Park (Llamas and Martínez-Santos 2005; Martínez-Santos, de Stefano et al. 2008). Although hydrological and climatic factors (e.g. droughts) are important to understand particular aspects of the problem, the decreasing groundwater level is strongly related to changes in farming land-use patterns; that is, changes in crops planted and in irrigation technology used determine the amount of water that is pumped from the aquifer and "lost" due to evapotranspiration. A sustainable situation can not be reached without significant changes in agricultural water use for irrigation (Bromley, Cruces et al. 2001; Lopez Sanz 1999).

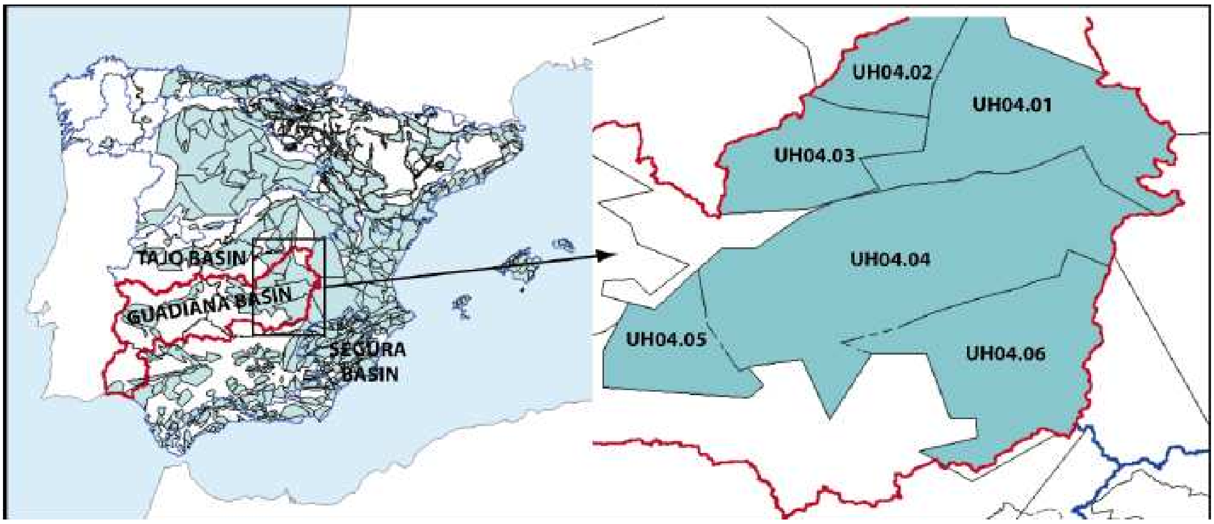

Figure 5: The location of the Mancha Occidental Aquifer (in the figure: UH04.04) in the Upper Guadiana Basin (source: Llamas and Martinez-Santos (2005)).

The overall dynamics can be ascribed to a combination of factors and developments on multiple levels. Figure 6 gives a structured view on the developments since the 1970s using the subsystem typology introduced in paper 3 ("specifying regime") and assigning the subsystems to (administrative) levels. In the UGB case one natural subsystem is considered, the MOA. Farmers constitute the only action subsystem (considered) and farmers are influenced through three mostly distinct intervention subsystems on the EU level, the national level and the regional level.

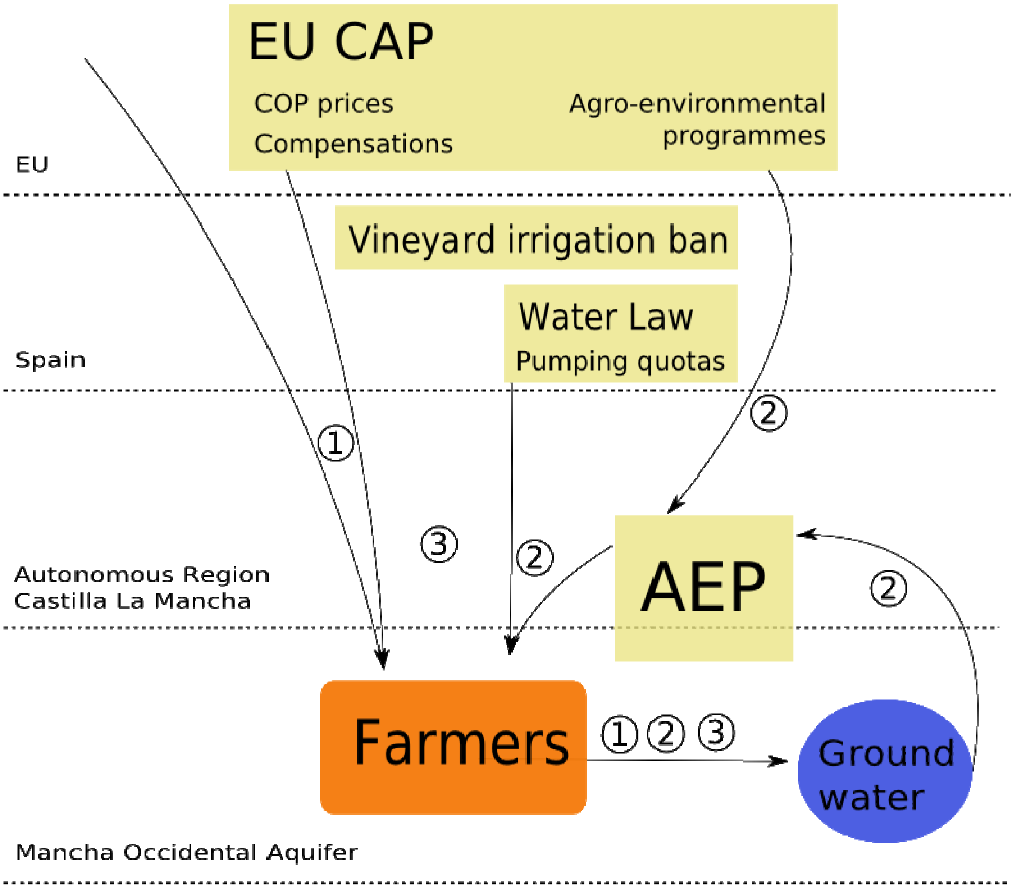

Figure 6: Influences from various levels shape the development of irrigated agriculture in the Mancha Occidental Aquifer. Intervention subsystems are represented through institutions generated. Numbers indicate in which process phase the respective subsystems are involved (see text).

Roughly three phases can be distinguished (see figure 6): 1) irrigation and pumping technology became widespread since the 1970s. Irrigated agriculture encompassed the possibility to plant water-intensive crops like corn, alfalfa and melons which did not grow in the region before that time. It further provided the possibility to achieve higher yields of traditional crops like winter wheat, barley, vineyards and olives. Formal rules have also been changing; most notably the EU Common Agricultural Policy (CAP), which Spain joined in 1985, had considerable influence on profitability of various kinds of crops, during some periods favouring water-intensive crops, especially corn (Varela-Ortega 2007). 2) In 1985 a new national water law was introduced and water passed from being a private good to be publicly owned. This law also introduced the possibility that river basin authorities restrict groundwater extractions. To counteract over-exploitation in the MOA, since the early 1990s pumping of groundwater was legally restricted, well-drilling was banned and users were required to organize themselves in water user associations (Llamas and Martínez-Santos 2005). However, the drastic reductions in allowable quotas led to considerable social unrest and many farmers disagreed with the obligatory pumping restrictions and took more water than granted (Llamas and Martínez-Santos 2005; WWF 2006; Varela-Ortega

2007). Actually, in certain groups of especially smaller farmers a norm has established that a restriction of previously unlimited water usage is not a rightful act. This led to conflict between "legal" and "illegal" farmers. Confronting farmers is politically sensitive in this rural area and consequently control of pumping is limited. It is estimated that nowadays illegal extractions still account for the larger share of groundwater extractions (Llamas and Garrido 2007). An agro-environmental programme (AEP) that compensated farmers for voluntarily reducing groundwater extractions was more successful in temporarily reducing the irrigated area and groundwater extractions. It was set up under the Agro-environmental scheme of CAP regulation 2078/92 in cooperation between the Regional Government and the EU. However, this programme was highly funding intensive and not in line with water policies, partly allowing higher levels of extractions than the pumping quotas since water quotas under the AEP were not differentiated according to farm sizes (Varela-Ortega 2007). 3) The AEP's compensatory payments were reduced and allowed water extractions were brought in accordance with pumping quotas. Further, under the CAP, intervention prices were further decreased and respective compensatory payments increased. And a national law banishing the irrigation of vineyards was abolished[9]. Those developments lead to a renewed increase of the irrigated area and of water extractions to a non-sustainable level. Current endeavours in the region aim at reducing the environmental burden without constraining socio-economic prosperity too much (Confederación Hidrográfica del Guadiana 2008; Martínez-Santos, Llamas et al. 2008).

This overview of the process in the UGB shows that the transformation of rainfed agriculture into irrigated agriculture involved multiple levels (EU, national, regional, local), multiple factors (technologies, crop types, groundwater level, regulations, subsidies, norms) and several actors (farmers, environmental groups, governmental actors on various levels and in various domains). During the development of irrigated agriculture, farmers have acquired knowledge and have built up a stock of technologies. Irrigated agriculture has brought labour and modest wealth to a previously poor and depressed region (Llamas and Martínez-Santos 2005). New institutions like groundwater user associations have been introduced. The conflict over groundwater also formed new social groups like "legal" and "illegal" farmers (with respect to pumping quotas) and increased the importance of environmental groups. Although the region is struggling with restricting irrigation to a sustainable level and thus the system has not yet stabilized, the fact that irrigated agriculture has introduced fundamental changes and is now an essential part of the regions economy and social life is unquestionable.

[9] Although vineyards are a dominant crop in the UGB, the effect of this policy change must be seen in light of previous developments. Vine farmers could not claim water rights based on previous usage when groundwater was declared publicly owned in 1985 (because irrigating vineyards was illegal, so vine farmers were supposed not to use groundwater), therefore they did not have legal water available once the irrigation of vineyards was allowed. Still, many vineyards were already irrigated using "illegal" water anyway.

The process is path-dependent and has lead to a certain stabilization of the system in its transformed state. It has involved technical as well as social/cultural elements and control over the process has been distributed. Top-down policies like the pumping quotas could not solve the problem of groundwater over-exploitation and nowadays new modes of governance including stakeholder-involvement are adopted to find ways towards a sustainable future. Given these characteristics, this process is considered to fall into the realm of interest of research on system innovations.

The model

The model is presented in paper 4 ("Guadiana model"). The purpose of the Guadiana model is to provide an explanation for the observed transition from rainfed to irrigated agriculture. The idea behind this aspiration is that an enhanced understanding of the system provides valuable information for future policy making. The case specific literature provides information on driving forces (technological development, changes in regulations) and consequences (amount of irrigation) but it leaves a gap in explaining how e.g. a change in regulation leads to the corresponding observed consequences. The model addresses this gap by focussing on the farmers which "translate" context into changes in irrigated area and water use. The model is developed in a modular way that allows studying impacts of variation of the implementation (especially of the actor model) in order to account for epistemic uncertainty. The article is however restricted to present the overall model structure and some simulation results obtained from the first realised model implementation.

The model comprises the regulations which are the output of several intervention subsystems (see figure 6 above) as predefined scenarios changing parameters of relevance for farmers (e.g. prices, amount of legal water). The output of the model gives the impact on the natural subsystem but consequences (effect on wetlands) are however not captured by the model. The action subsystem of farmers is the dynamic part of the model. It is defined based on insights gained through literature review. The model explains farmers' behaviour as depending on the respective farmer's characteristics, namely weights attached to a list of priorities (having a high gross margin, having low risk, having low labour loads, staying legal), the size of the farm, the accumulated stock of irrigation technology and a farmer's knowledge. Those characteristics unfold their significance in the context in which the farmer acts. This context comprises options (crops, irrigation technologies) and rules and is identical for all farmers. The model considers the diffusion of innovations in the population of farmers as well as path-dependency of the decisions of single farmers (due to having specific skills and prior investments). A modular decision-making algorithm represents farmers' choice of land-uses. In brief, it comprises the following steps: 1) a set of considered options is identified; 2) a set of potential future land-use patterns is created; 3) land-use patterns which are too different from the current year's land-use pattern are discarded; 4) consequences arising from formal rules are evaluated for each of the remaining patterns; 5) the utility-maximizing land-use pattern is selected. Parameters can be varied to study the influence of the weights farmers' attach to different priorities.

The model runs in steps of one year. Each year, each farmer chooses a land-use pattern. The development of aggregated crop patterns, the usage of irrigation technology and the amount of ground-water used are outcomes of model runs which can be compared to empirical developments.

The model uses aggregated empirical information on water extractions and on the irrigated area to calibrate (and validate) the model. This information is however not considered sufficiently specific to mitigate the problem of equifinality. Many different land-use patterns (a land-use is a combination of a crop and a technology) may result in the same amount of irrigation. However, if it comes to "what-if" questions - e.g. what would have happened if vine irrigation was not banished before 1997 or if the CAP would not have favoured maize - which nowadays may be posed in a similar way regarding the future of the Upper Guadiana, then it makes of course a tremendous difference if water is used for vineyards or for cereals and horticultural crops. Hence only using water extractions and irrigated area as aggregated information was not considered sufficient to derive an explanation. Consequently more specific information on land-uses, especially time-series of the areas of different types of irrigated crops, was used complementary.

The main findings are that no single factor is sufficient to explain the empirically observed land-use changes but that interactions of factors have to be considered. Distinct "logics of production", farms which exhibit similar factor combinations, are identified and it is shown that these different types of farms can be expected to exhibit distinct responses to drivers of land-use change. It is therefore important to acknowledge heterogeneity of farm types when aiming at influencing land-use changes. Although some of the more specific findings of the modelling exercise are open to debate due to methodological reasons, it can be concluded that a sound understanding of the social system making use of a resource is required to solve problems of resource over-use.

The model was derived with the goal to remain modestly complex. Still, it is on the edge of remaining transparent. It can be argued that the model is not overly complex compared to the real system's structure. The reasoning is that models which feature more than necessary parameters can usually be "tweaked" to reproduce some observed aggregated dynamics. In contrast to that, in the modelling exercise reported in paper 4 reproduction of land-use patterns could not capture significant dynamics. Assuming that the model is not simply wrong it follows that the complexity used in this model seems to be not too high for capturing (only) the essentials of this system. Hence the complexity of this model allows some informed judgement of the complexity of an action subsystem and of the detail required for explaining its dynamics. The conclusions derived from this observation regarding the research questions posed in this thesis are embedded in the synthesis in the next chapter 5.

Chapter 5: Synthesis

The papers outlined in the previous chapter contain the main work done during the development of this thesis. Due to the organization in research articles, the answers to the research questions of this thesis are somewhat scattered. This chapter synthesises the contribution of this thesis with regards to the research questions formulated in the introduction. RQ 2 is answered first, then RQ 3 and finally the most encompassing RQ 1.

5.1 RQ 2: Does the topic of system innovations pose specific challenges to model development?

Equifinality frustrates insights on mechanisms underlying system innovations

The conceptual and theoretical discussions in papers 1 ("challenges and opportunities") and 2 ("current state") highlight the vast scope and complexity of system innovations, their inherent uncertainty and the limitations of our understanding rooted in the underdeveloped knowledge base of this young research field. This poses a challenge for model development since on the one hand the vast scope and inherent complexity of system innovations allow for a multitude of model structures, while on the other hand the amount of data and stylized facts to rule out competing explanations are limited. The resultant coexistence of several reasonable explanations of the same empirical phenomenon rooted in a many-to-one relation between system structure and emergent behaviour is a well-known problem for studying complex systems but paper 1 ("challenges and opportunities") points out that it is especially pronounced regarding transition modelling and that the bandwidth of possible explanations is especially broad in this field. Concepts utilised in empirical studies of system innovations are defined rather broadly and qualitatively with no existing operationalization into measurable quantitative units and the defining characteristics of system innovations as framed by transition researchers (e.g. S-form) are very broad and can easily be reproduced by a wide range of models. Using case-studies is essential to increase the amount of information available for foundation of a model's structure and for validation. However, even if qualitative empirical studies are used as base for model development, they can be translated into computer models using different analytical tools resulting in different model structures (cf. Bergman, Haxeltine et al. 2008 and Yücel and van Daalen 2008 for two structurally different models of the transition from sailing ship to steam ship). Further, if case studies are utilized to inform model development, usually the information available is used to structure and calibrate the model and can thus no longer be used for validation. These methodological challenges are also clearly illustrated in paper 4 ("Guadiana model"). Even regarding farmer behaviour which has been studied by various strands of the social sciences since decades, knowledge usable for the micro-foundation of this case-specific model is limited (e.g. regarding an appropriate actor model and relevant factors to be considered). Calibration and validation could not be clearly separated since the limited knowledge of the micro-level requires utilisation of knowledge of macro-level developments for model calibration. Further, only one macro-level data set has been available due to contingency and historicity of the phenomenon investigated and hence no independent macro-level data was available for validation.

Overall, the challenges involved in specifying a model’s structure and in validation lead to the acknowledgement of the co-existence of potentially many reasonable representations of system innovations what is reflected in the multitude of different structures of the models reviewed in paper 2 ("current state"). A drawback of such a diversity of model structures is that different and sometimes contradictory conclusions are drawn in the respective modelling exercises. Increasing returns to scale turn out to be a central mechanism in some exercises (Weisbuch, Buskens et al. 2008; Yücel and Chiong Meza 2008), while others manage to generate "transitions" without explicitly considering this (Schilperoord, Rotmans et al. 2008; Timmermans 2008). Similarly, while the model of Schilperoord, Rotmans et al. (2008) does not generate transitions without a landscape signal stimulating this, de Haan (2008) and Timmermans (2008) admit the absence of a landscape level in their models, but still generate dynamics they consider being transitions (or first phases of transitions, in case of de Haan). The comparison of those models shows that modelling exercises starting from different basic assumptions may well lead to different conclusions on how some overall system dynamics can be explained. Despite all their differences in model structure and in results obtained, all models present some evidence that lends them some plausibility. It is difficult to assess the added value of each model and to derive general insights on mechanisms underlying system innovations.

Micro-macro interactions are essential

Transitions are regime changes and this comprises disintegration of an old regime and creation of a new one – they are processes of decay and (re-)creation of structures. In these processes macro-level changes emerge from micro-level developments while macro-level developments influence the micro-level. It is therefore argued in paper 2 ("current state") that micro-macro-interactions are essential for understanding system innovations. But at the same our understanding of involved processes is limited and few formalized representations exist.

The importance of macro-level structures (i.e. regime, niches) influencing a micro-level of entities and channelling developments into specific directions is common ground in transition research (as reflected in the importance of the MLP). But, as Geels states: *"Although processes at different levels can converge and create windows of opportunity for regime change, the actual linkages* *always need to be made by actors. Hence, the MLP needs to be filled in with more detailed actor-related patterns.*" (Geels 2005b, p. 692). Hence, for an explanation of a system innovation– which requires specification of acting entities – it is not sufficient to take macro structures like regimes and niches as given but the micro-level entities, especially actors, have to be considered. Another argument to underline the importance of actors is that a crucial phase of system innovations starts when the dominant regime begins to loosen and thus looses its coordinative function. Regime resources are redistributed partly depending on regime actors' activities. Empirically it can be observed that actors may stick to the regime and try to defend their position e.g. through technological improvements (the sailing ship effect). But it can also be observed that actors diversify into various technologies; or that different regime actors follow different strategies (Geels 2005b).

Two types of actor interactions which are important for micro-macro interactions can be distinguished. One type is aggregated and self-organized behaviour of many myopic actors leading to emergent outcomes on the macro-level. Consumer behaviour and also competition of many small firms may be represented through such collective behaviour. Several models exist, like diffusion of innovation models or threshold models of collective behaviour (Granovetter 1978). But actors' interactions during policy development or the interaction of multi-national "big players" can not be appropriately captured by such models. They are better represented by the other type of actor interaction which can be abstracted as interaction of few, reflexive actors – as "strategic games". According to Mayntz (2004), the toolbox to analyse and systematize constellations of corporate actors and institutional settings is not very well filled; considering them in models is thus challenging. Another challenge associated with the latter type of actor interactions arises from the fact that reflexive actors are able to perceive patterns on the macro-level and may behave in a strategic way in order to maintain or change the macro-situation. This leads to so-called "second-order emergence" (Squazzoni, 2008a) which is a unique feature of social systems which differentiates them from natural and biological complex systems (Mayntz 2000). The representation of reflexive actors in a model adds however a further level of complexity on the micro-level by including intentionality and cognitive properties.

Both types of actor interactions play a role in system innovations although their respective importance may vary depending on the field in which system innovations are analyzed. Some sectors like water management feature mostly corporate actors while in others like mobility and agriculture the role of many, mostly unorganized actors like consumers and farmers becomes prominent. Considering both types of actor interactions is in line with a general insight that social macro phenomena are usually the outcome of an interaction of planned and unplanned actions. Most often several actors act strategically in order to influence the macro-situation in a specific direction (e.g. a new law is passed, a campaign is started), but the actual emergent outcome (further

influenced probably through myopic actions of still other actors) is different from all intended outcomes (Mayntz 2009).
(Strategic) actor interactions are not the only way in which the micro-and the macro-level interact. Complementarities between technologies, standards defined according to best practices and mutual dependence of provision of infrastructure and spread of associated artefacts are other examples.
In general, micro-macro-interactions and processes which align entities into macro-structures are manifold, diverse and to my knowledge not (yet) analysed systematically and availability of formal models is limited (see chapter 3.1 and paper 2 "current state"). Micro-macro-interactions are essential for understanding system innovations but at the same time pose challenges for modelling.

5.2 RQ 3: How to represent coupled human-technology-environment systems in models?

Models are composed of interacting elements which must be considered again (sub-) models of some part of the overall system. For example, each farm in the Guadiana model presented in paper 4 is a model of a real farm representing this farm through some attributes (e.g. size of farm) and the implemented process of land-use pattern generation. The rationale behind this representation is that it is assumed that this model of the farm constitutes a reasonable simplification with respect to the purpose of the overall model. No methodology exists to identify the "best" or at least a reasonable representation of a system. As a rule of thumb, when defining model elements and interactions, simplification should be as high as possible in order to reduce overall model complexity while at the same time a model should not oversimplify matters and shroud system aspects which are essential for the purpose of the model.
So, what is a reasonable subdivision of coupled human-technology-environment systems into model elements and interactions? Paper 1 ("challenges and opportunities") points out that this can not be answered in general but must be seen in light of the model purpose. The vast scope and the complexity of HTE-systems frustrate any attempt to represent "the system" in an "in silicio" replication of the real system. This reflects a general insight from complexity studies. The model purpose is a necessary guideline to distinguish parts and aspects of a system which need to be captured from negligible ones. For example, in a model calculating the CO_2 emissions of the German car fleet, the distribution of fuel consumption of cars will be relevant while the distribution of colours is not.
However, having made this point, it must also be said that systems often suggest some "natural" subdivision. For example, if analysing the dynamics in a group of people, a "natural" subsystem is the individual. If analysing more encompassing systems, this is often less clear, for example nation states may for example be represented through referring to the individuals, but they may also be represented through various institutions (formal and informal rules, e.g. the constitutional law) and social groups or as network of regions and cities. Regarding the representation of HTE-systems

three different kinds of subdivision are identified and some pros and cons are discussed in the following: a) functional subsystems as described in paper 3 ("specifying regime"), further b) niches, regimes and landscape as suggested by the multi-level perspective and c) entities and interactions.

Functional subsystems

System innovations comprise several domains which have been abstracted in paper 3 ("specifying regime") into three different types of subsystems which are governed by different types of change processes: natural subsystems, action subsystems and intervention subsystems. Natural subsystems are viewed as mostly passive resources or sinks; however ecosystem dynamics may lead to non-linear reactions to external stimuli. Action subsystems refer to many similar actors producing products, providing services or using/consuming products. In action subsystems processes of collective behaviour (diffusion of innovations, emergence of norms) are of major interest. Intervention subsystems shape action subsystems through creating formal institutions (laws, regulations etc.). Power issues and negotiations between actors having partly contrary interest are of major relevance. Models could abstract macro-behaviour of these different types of subsystems and focus on subsystem interdependencies. Weisbuch, Buskens et al. (2008) is an example of an abstract representation of interactions between production and consumption regarding the introduction of "green" cars.

Conflating many actors and factors into aggregated behaviour of subsystems probably allows representation of the "big picture" of system innovations and maintains transparency, but at the same time considerably (over-) simplifies many processes central to system innovations. Aggregated descriptions like simple diffusion models or learning curves relate a target variable (e.g. the number of adopters of an innovation, the price of a product) to one or very few input parameters while implicitly keeping several other context elements static. In contrast to that, transition researchers have highlighted the interdependency and co-evolution of multiple factors. System innovations like e.g. a transition to a "customized mobility" system which comprises a combination of private and public transport, utilizing different vehicles for various purposes and making use of information technology to coordinate trips (e.g. Kemp and Rotmans 2004) require several interdependent changes within and between subsystems. Models based on aggregated representations of functional subsystems are too static and inflexible to capture such radical multi-dimensional changes.

Multi-level perspective

The multi-level perspective (MLP) has been introduced in chapter 2.2. It has been widely applied in a range of empirical studies and found to be suitable to describe system innovations. The

MATISSE[10] model and de Haan (2008) have used this subdivision in their models. Adopting such a representation has the advantage of being close to empirical studies what potentially provides some advantages when defining the model structure and comparing simulation results to empirical observations. However, it must also be noted that in empirical studies the three levels of the MLP are usually not precisely defined but used as heuristics. Often, not much space is devoted to defining and describing what a regime or niche is. Such configurations are often framed based on intuition and important assumptions (e.g. boundaries, key issues) are not further questioned once defined. However, what actually is "the regime" (or the niches) is not given through some kind of clear system boundaries but is a matter of framing and deliberation and the choices made may well influence the subsequent analysis. In this context, paper 3 ("specifying regime") proposes five characteristics to more deliberately specify regimes: 1) purpose: regimes relate to a societal function; 2) coherence: regime elements are closely interrelated 3) stability: regimes are dynamically stable 4) non-guidance: they show emergent behaviour and 5) autonomy: they are autonomous in the sense that system development is mostly driven by internal processes. The actual degree to which the characteristics are exhibited by different regimes is expected to vary and this can partly be influenced while framing the regime; by widening or narrowing the scope of analysis. The characteristics hence facilitate a discussion about traits of various regime framings.

Still, there clearly is some gap between the concepts and the empirical studies and the representation of regimes and niches in computer models. For representation in a computer model, the abstract concepts need to be further specified and operationalized. The specifications in de Haan (2008) and in the MATISSE model involve some location of regimes and niches in a "practice space" (e.g. spanned by two axes like price and CO_2 emissions), accumulation of "power" depending on support received based on the location in the practice space and use of this power in order to maintain or increase support. A representation of some practice space offers the possibility to relate structurally different configurations (e.g. individual transport based on fuel-cell cars compared to customized mobility) and provides a means for an intuitively understandable representation of ongoing processes. The processes of power accumulation, of movement of regimes and niches in the practice space and of niche-regime interactions are however coarse simplifications of the variety of processes observed in empirical transition studies and introduce many black-boxes (see paper 2 "current state"). The model elements and processes (in the MATISSE model e.g.: "institutional capacity" of regimes and niches and "transformation of a niche to an empowered niche") are somewhat artificial and not (explicitly) related to empirical evidence and the appropriateness of utilised theories is not discussed. Moreover, the models require the artificial assumptions of ascribing actor-like coherence and the ability to act to regimes and niches.

[10] When discussing recently developed models, the term "the MATISSE model" is sometimes used to refer to a set of publications being based on the same model: Schilperoord, Rotmans et al. (2008); Bergman, Haxeltine et al. (2008); Köhler, Whitmarsh et al. (2009).

This is done in the sense of capturing emergent behaviour arising from the activities of many involved actors. This assumes a coordinative role of macro structures; otherwise over time the regimes’ and niches’ practices would disperse all over the practice space. As outlined in the answer to RQ 2, such a strong coordinative function of a regime is at least questionable once the regime starts to loosen. Paper 2 ("current state") thus has argued that models directly using niches and regimes as model elements fall short in capturing the complex micro-macro interactions involved in the decay and (re-)creation of structures in system innovation processes. Further, a model based on regimes and niches which can not be (in principle) disaggregated to a level which involves entities to which intentional behaviour can be accredited does not meet the criteria for a complete explanation as defined in chapter 2.1.

Entities

On a lower analytical level, system innovations comprise many entities (actors, technologies, institutions etc.). Representing explicitly actors separate from a physical world (technology, infrastructure, nature) and institutions avoids the problem of oversimplification through aggregation. Main features influencing change processes such as innovativeness of adopters, information channels in diffusion processes, heterogeneity of (changing) preferences, multiple attributes of options’ (e.g. price, CO_2 emissions), increasing returns to adoption, search heuristics in technological development, competition between firms, investment decision of firms, specific institutions like regulations or norms etc. all can be represented explicitly and full credit can be given to the potential of peculiarities to influence overall dynamics in a complex system. Further, in principle, choosing a representation on the entity level allows to incorporate alignment of entities into structures and to consider the micro-macro interactions discussed when answering RQ 2.

However, the downside is that still complexity needs to be reduced to achieve methodologically manageable models. One possibility for doing so is to (again) aggregate actors and elements. Yücel and Chiong Meza (2008) have used system dynamics (SD) to study transitions. SD models represent average values of variables (e.g. average actor behaviour) what implies a loss of heterogeneity and any related complex dynamics. However, Yücel and van Daalen (2008), modelling the transition from sailing ship to steam ship, introduce in a SD model different groups of actors, e.g. seven different user groups. This shows that this approach can be stretched and aggregation can be balanced with model complexity. Another possibility to reduce complexity is focussing on one subsystem. The model of the transition in the Upper Guadiana presented in paper 4 is such an exercise focussing on a single dynamic action subsystem – the farms – while externalizing dynamics in other subsystems into the changing but predefined context of farms.

Paper 1 ("challenges and opportunities") and 2 ("current state") recommend to follow a strategy of complexity reduction through abandoning the goal to model an overall system innovation. The answer to RQ 1 below elaborates more on that and specifically on the usage of models as thinking tools and on the utilization of building blocks of understanding for designing model exercises.

5.3 RQ 1: What can models contribute to an understanding of system innovations in coupled human-technology-environment systems?

Models are useful as thinking tools

The lesson learned from the review of recent models (see answer to RQ 2 and paper 2 "current state") is that given the diversity of model structures, obviously some convergence, combination and refinement is needed to reach common ground. The conceptual and theoretical discussion of equifinality (see answer to RQ3) has shown that substantial challenges exist on this way which can not easily be resolved. It has further been argued that the reviewed models seem strongly simplified in light of the richness of entities and interaction patterns considered in conceptual and empirical work and that those models neglect essential micro-macro interactions. Insisting on the sufficiency of one of the proposed model structures to capture the essentials of a generative mechanism and to explain a system innovation would mean to question the relevance of most of the entities and interactions identified in conceptual and empirical work. If there is a point in emphasizing the role of micro-macro interactions and in identifying such a diversity of micro-level entities and interactions contributing to the formation of structures, then it must be concluded that hitherto models representing overall system innovations do not appropriately capture the constellations of entities and interactions which generate the respective process. More likely they generate similar macro-dynamics as observed in system innovations but the model structure does not appropriately resemble the underlying system structure. Such resemblance of system structure and model structure would however be required for an explanation and further is inevitable for model exercises venturing beyond the context used to specify and calibrate the model (e.g. prospective studies, abstract studies comparing influence of alternative policies). Only if the model structure resembles the system's structure it can be expected that the model's response to some previously untested stimulus is (to a certain degree) in accordance with the real system's response. It has been concluded in paper 2 ("current state") that the gap between the multitude of micro-level entities and processes and the overall emergent system innovations seems to be too big to be captured by one big "jump", i.e. by one model aiming to explain a system innovation in its totality.

Still models can be useful. Paper 1 ("challenges and opportunities") has argued that models of system innovations must be considered being most useful as thinking tools. The following two examples may show how using models as thinking tools may contribute to an enhanced understanding of system innovations. The MATISSE model uses the multi-level perspective (MLP) and the typology of transition pathways derived by Geels and Schot (2007) (briefly introduced in chapter 2.2). In Bergman, Haxeltine et al. (2008) it is shown that the proposed typology of timing and kind of multi-level interactions indeed results in the different transition pathways as suggested by Geels and Schot. This must however be considered a weak confirmation only since the translation of the underlying concepts into a computer model incorporates several degrees of freedom which may be used during model design and calibration to align simulation results with intended dynamics. But, there is another interesting aspect of the MATISSE model. While implementing the multi-level perspective, another level was introduced in addition to niche, regime and landscape, the "empowered niche". Empowered niches are conceptualized as differing from other niches regarding their strategy. While niches are considered defensive, empowered niches offensively attack the dominant regime. This differentiation of niches was considered useful during model development. It constitutes a conceptual refinement which may stimulate empirical research which may corroborate the distinction made and may eventually lead to an enhancement of the multi-level perspective.

The Guadiana model of land-use change in an agricultural system presented in paper 4 uses case-specific knowledge to select model building blocks from the literature which are considered fruitful to explain the transition from rainfed to irrigated agriculture. The innovative contribution of this model is to analyse the role of behavioural aspects for the spreading of irrigated agriculture while at the same time acknowledging and considering the importance of changing rules and of diffusion processes. The Guadiana Model facilitates to test assumptions and to scrutinize intuitively plausible explanations for land-use change. For example, this model questions that factors such as gross margin, sunk costs and necessary investments, lacking skills or risk in isolation provide a sufficient explanation for the empirically observed land-use changes. It further underlines the importance of acknowledging heterogeneity of farmers when aiming at influencing land-use changes. These insights suggest that a customised representation of actors' behaviour is essential for modelling (parts of) system innovations on the micro-level of entities.

Implications for the scope of models

Using models as thinking tools entails some implications for model development. The model structure and the simulation results must be comprehended sufficiently well to understand how certain assumptions lead to some observed overall behaviour or system property. This requires transparency of models (see paper 1 "challenges and opportunities"). "Transparency" refers to the possibility of relating simulation results to particular characteristics of the model structure and assumptions made; generating insights on how those contribute to observed dynamics and properties. If models are transparent, insights can be abstracted from the specific model used to gain them. In this way, transparent models contribute significantly to the knowledge base of the modelled system(s). However, the broader the scope of a model, the more elements and interactions must potentially be included in a model and hence the more degrees of freedom exist when defining the model structure. Then, in complex (model) systems small changes may have big effects and therefore each subjective choice made during model development may change the results of the modelling exercise and must be understood in context of all other choices made. Consequently, in the realm of complexity, only parsimonious models are transparent. Given the vast scope and complexity of system innovations, any model which shall be parsimonious enough to reduce degrees of freedom strongly enough to maintain transparency necessarily must neglect or considerably simplify some aspects. The experience with the Guadiana model underlines this argument. This model represents (only) one action subsystem as dynamic model part and represents this action subsystem with a level of detail as considered necessary to provide an explanation of observed land-use changes (see chapter 4). The experience with working with the model makes clear that its complexity is on the edge of remaining transparent. Model behaviour had to be explored in a stepwise manner to achieve an understanding of the model's dynamics. Further, the parameter space of this model is already too vast to be fully explored but empirical evidence had to be used to define meaningful parameter sets around which some local sensitivity analysis could be performed.

Given the necessity to reduce a model's scope in order to achieve transparency, it is recommended in paper 2 ("current state") to abandon the idea to model overall system innovations. It is instead proposed to use models to scrutinize concepts and assumptions of transition research and to make use of building blocks of an intermediate level of complexity. The reasoning is that on the one hand HTE-systems in different areas (e.g. agriculture compared to mobility) involve different types of entities and hence require consideration of these differences in respective explanations but that on the other hand similarities exist which can be generalised across (some) cases. Using building blocks of explanation rendering classes and characteristics of (sub-) processes of system innovations may be a suitable strategy to cope with the contingent and idiosyncratic nature of social processes in general and of system innovations in particular while not "reinventing the wheel" for each further case-study. Conceptual, empirical and theoretical work in transition research has identified a bunch of such building blocks for understanding system innovations, which can partly also be found back in the reviewed transition models. On a high level of abstraction those are for example the relevance of the kind and timing of multi-level (Geels and Schot 2007) and multi-domain interactions (Nill, Haum and Hirschl 2004; Kingdon 1995; Konrad, Truffer et al. 2008), the role of visions and expectations (Berkhout 2006; Truffer, Voß et al. 2008), the role of transition contexts (Smith, Stirling et al. 2005) and potentially still others. On lower abstraction levels one finds recurrent patterns as e.g. self-reinforcement of option prevalence through heterogeneous actors and increasing returns to scale, the patterns of interactions of technologies and actors identified in Geels (2005b) and by Hillman (2008) and also many insights from disciplines integrated in transition research (see e.g. Geels 2004 for relations between actors, rules and technologies and respective references to strands of literature dealing with those relations).

Building blocks constitute a middle ground between the micro-level and overall system innovation dynamics and can help to connect those other levels in two ways: first, they specify classes of similar micro-level constellations and provide a scheme to study those. For example, when studying interactions between regimes and niches, the conceptual distinction between structural coupling (via actors involved, elements shared) and functional coupling (e.g. via competition for resources and markets) might guide the analysis. In turn, micro-level studies likely will enhance understanding of building blocks (e.g. identify other types of couplings). Second, building blocks potentially allow for (careful) abstraction of constituting micro-processes when analysing overall dynamics; e.g. structural coupling and functional coupling might abstract different mechanisms how niches may pressure a regime. Such building blocks may eventually be combined to explain system innovation cases based on the specificities of that case entailing a particular form and relevance of the (interaction) of those building blocks; while explanations of the processes underlying each building block are available if a regression to lower levels of abstraction is required. Through this partitioning of an overall complete explanation, building blocks facilitate deriving a complete explanation without entering the realm of excessive complexity. Paper 2 ("current state") suggests that the task for the future is to enhance our understanding of such building blocks, to relate them, to identify the contexts and situations in which each of them becomes relevant and to explicate their role in the overall process.

Models can help to relate characteristics and concepts used in building blocks to micro-level entities. For example the transition contexts distinguished by Smith, Stirling et al. (2005) make a distinction between cases along the axis of "high" or "low coordination" of regime actors. Models can be used to study which entities and processes are involved in generating such emergent properties like coordination. Models might further be used to study the relation between building blocks, for example how the conceptual distinction between structural coupling and functional coupling of niches and regimes (see above) enriches the picture of kind and timing of multi-level interactions according to Geels and Schot (2007). This latter idea to study the relation between building blocks without causal regression to the level of entities rests however upon the assumption that building blocks can be represented and related on a higher level of aggregation without neglecting essential interactions. Hence, analysing the combination of building blocks requires first of all a sound understanding of each building block involved. This understanding may serve to define appropriate abstractions which adequately capture the respective role of a building block in various contexts. The challenge to identify, specify, understand and relate conceptual building blocks could be an agenda for transition modelling for the coming years[11].

Two more specific approaches are suggested in paper 2 ("current state"): simulating historical cases and scrutinizing proposed general mechanisms. Simulating historical cases refers to replicating

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[11] It should be noted that although some of the reviewed models have implemented some of the building blocks mentioned above, the agenda suggested here is different from what has been done in most of those exercises. The objectives of hitherto models have been diverse (e.g. testing a method, prospective studies, assessing policies) and hence most studies did not directly aim at enhancing our understanding of conceptual building blocks (exceptions are de Haan 2008 and Weisbuch, Buskens et al. 2008)

qualitative studies utilizing some conceptual framework to structure their work. The objective of a related model exercise could be to put the utilised framework to a test, using the precision required for model building and the possibility to relate structure and dynamics to identify elements and processes which may have been neglected in the narrative. This may help to identify gaps in the conceptual frameworks used to structure the narrative. The "empowered niche" introduced in the MATISSE model may be such a case, although this result seems to be rather a by-product of model development which has not received much further attention yet.

The other suggestion is to use models to scrutinize proposed general mechanisms. Weisbuch, Buskens and Vuong (2008) is an example of such a modelling exercise which advances our understanding on the interplay of heterogeneity of actors, increasing returns and the occurrence of multiple attractors in technological substitution. Simulation models can be used to study such links between structure and dynamics. The robustness of the results of such modelling exercises should ideally be corroborated through sensitivity analysis assessing the influence of changes in (uncertain) parameter values but also through variation of assumptions introduced while translating the underlying concepts into a computer simulation model.

5.4 Further research opportunities

Modelling system innovations is a highly dynamic young field and several new questions have arisen during the development of this thesis which could not be answered in the given amount of time. Anyway, since this thesis' aim is to identify the potential of applying computer simulation models for studying system innovations such open issues are helpful to identify opportunities for further research.

Paper 2 ("current state") has discussed some short-comings of hitherto modelling exercises. Emergent self-stabilizing macro-entities are central to many transition cases in the literature and are central to current transition theorizing. What is missing in hitherto models is an explanation how mutual adaptation of entities of different domains leads to integrated "configurations that work" (i.e. niches, regimes) which then eventually compete on a higher level and influence the micro-level in a way that sustains their existence. That is, no model explicitly explains how micro-elements form niches and regimes and how those influence in turn the micro-level. This micro-macro interdependency constitutes a major issue open for future research. Sawyer (2003) relates multi-agent systems to the micro-macro link in sociological theory and concludes that there are simulations that show how macro-social phenomena emerge from individual action and such that demonstrate that a change of macro-structure (e.g. network topology, size of a society, communication mechanism) changes the bottom-up processes of micro-to-macro emergence. He then argues that no simulation has combined both micro-to-macro and macro-to-micro processes simultaneously and that hence no (agent-based) model has yet fully implemented a micro-macro link underlying some sociological phenomenon[12]. Such a full implementation of the micro-macro link would be required to fully capture the emergent decay and re-creation of structure during system innovations in a model.

Another major challenge for the development and application of models of system innovations (which has been mostly skipped in this thesis) relates to the fact that politics and transition dynamics are strongly intertwined (Grin and Miltenburg 2009). This thesis has not explicitly dealt with the politics, or more generally with the governance of system innovations. It may only briefly be noted here that traditional ways of governance are not suitable to induce system innovations or to channel them into a specific direction. A caricature of traditional governance would be 1) analyze a problem, 2) identify policies potentially able to solve the problem, 3) predict outcomes of policies, 4) implement the most promising policy. Regarding the type of process discussed here, none of these steps seems feasible. There is no unique perspective on "the problem" (i.e. which developments are desirable); our understanding of the dynamics of the systems involved does not allow for clear identification of policies that would solve the problem and renders prediction of policy outcomes impossible; and often there is no single actor who has all the power to initiate changes in a certain direction. Alternative approaches have thus been suggested. Those approaches, like Adaptive Management (e.g. Folke, Hahn et al. 2005; Pahl-Wostl 2007a, 2007b) and Transition Management (Rothmans, Kemp et al. 2001a; Loorbach 2007; see also Smith and Sterling 2008; van der Brugge and van Rak 2007) feature aspects like inclusion of stakeholders, repeated reconsideration of ongoing developments and exploration of several paths before closing in to one solution. Whether following more a traditional "top-down" strategy or an alternative approach such as Adaptive Management or Transition Management, governance is on the one hand influential for dynamics of system innovations (e.g. through defining taxes, subsidies, laws, etc.) but on the other hand not (easily) accessible to modelling. The theoretical tool-box to formally represent specific types of corporate actor constellations is not very well filled since concrete macro processes involve a variety of structural and institutional features which is difficult to systematize (Mayntz 2004). That means theories and concepts being usable as base for an incorporation of governance of system innovations in models are mostly lacking.

The significance of the micro-macro interactions and the intertwinement of system innovations with their governance while spanning also other sectors (consumption, production) put the modelling of system innovations on the most challenging edge of the broader endeavour of understanding and modelling social systems.

In light of the challenges just outlined, in my view it seems clear that developing models of system innovations will remain a huge challenge in the near future and the role models of system innovations can play needs to be further explored and discussed. System innovations can not be

[12] But, regarding newer developments, see the results of the EMIL project (EMIL 2007).

predicted and also exploratory studies using scenarios to study system response under certain conditions needs to be carried out with caution due to the limited confidence that can be credited to the structures of such models. From my perspective, the most promising roles of models are on the one hand to generate insights on partial mechanisms relevant for system innovations that can flexibly and creatively be referred to and combined in the (qualitative) analysis of specific cases. This comprises all kinds of models not necessarily explicitly developed with respect to understanding system innovations. On the other hand, as outlined above, models can explicitly address the conceptual base of transition researchers, using the precision required for model building and the possibility to scrutinize relations between structure and corresponding dynamics to challenge and refine concepts.

Chapter 6: Conclusions

To my knowledge this thesis constitutes the first comprehensive assessment of the potential of applying computer simulation models to study system innovations. It adds to previous studies a consideration of the particular characteristics of system innovations which constitute challenges for model development. This provides a base for well-founded conclusions on the potential for fruitful application of simulation models. It further provides a more encompassing review of existing transition models than previous studies[13] and moreover relates the results of this review to empirical, conceptual and theoretical work in transition research. Different representations of coupled human-technology-environment systems (HTE-systems) have been abstracted into three types which have been discussed with respect to their advantages and limitations. Theoretical and conceptual work has been complemented by hands-on experience that made methodological and theoretical deliberations tangible. This thesis provides an introduction to and an overview of the field, assesses possibilities of applying simulation models, identifies challenges involved and suggests future routes.

System innovations feature several characteristics which put model-based approaches to this topic on the most challenging edge of the broader endeavour of understanding and modelling social systems. Those are the significance of emergent decay and re-creation of structure during system innovations involving multiple levels (at least entities and emergent structures such as regimes and niches); the vast scope of system innovations involving several types of subsystems (consumption, production, governance, nature); the intertwinement of system innovations with governance – a field which is hardly accessible to modelling; the complexity of the topic involving emergent behaviour of model systems and associated high sensitivity to assumptions and small perturbations; and the unpredictability of innovations.

In principle system innovations can be represented in models in different ways. Three different analytical subdivisions of HTE- systems have been identified: a) functional subsystems, b) niches, regimes and landscape as suggested by the multi-level perspective and c) micro-level entities (actors, technological artefacts, institutions, …). None of these representations is superior to the other ones per se but all feature some advantages and drawbacks. The model purpose is a necessary

[13] The only other overview of transition models I'm aware of is provided by Timmermans, de Haan et al. (2008) which in their introduction to a special issue on transition modelling in CMOT discuss the models presented in this special issue.

guideline to choose an appropriate representation and to distinguish parts and aspects of a system which need to be captured from negligible ones.

Modelling system innovations in HTE-systems is in its infancy. Hitherto model exercises have made some first steps but nowadays models are not yet elaborated enough to provide additional insights into the mechanisms underlying system innovations. Given the difficulties associated with specifying the micro-foundation of a model and the limited means for validation, the explanatory power of models is expected to remain low in the near future. Still, as the previous synthesis has shown, models can be useful as thinking tools, i.e. as additional means to scrutinize and refine concepts and to fuel debates.

Using models as thinking tools entails some implications for model development. In order to gain insights, models need to be transparent. Achieving transparency in a field as vast and complex as system innovations requires either very strong simplifications or restricting a model to some parts or aspects of an overall system innovation.

It is proposed to make use of building blocks of explanation of an intermediate level of complexity to define abstract model parts or to delineate certain aspects of an overall system innovation which should be studied using a computer simulation model. Several such building blocks have been identified in conceptual work on system innovations. It is suggested that the task for the future is to enhance our understanding of such building blocks, to relate them, to identify the contexts and situations in which each of them becomes relevant and to explicate their role in the overall system innovation. Indeed, the challenge to identify, specify, understand and relate conceptual building blocks could be an agenda for transition modelling for the coming years.

Modelling system innovations is a highly dynamic young field. Developing models of system innovations will remain a huge challenge in the near future and hence models should not be considered being silver bullets solving all problems of transition research. But this thesis has shown that they can be valuable tools contributing to the enhancement of the knowledge base of the field; little by little adding to answers of the "big questions". The specific role(s) models of system innovations can play in this endeavour needs to be further explored and discussed.

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Paper 1: Challenges and Opportunities

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Challenges and Opportunities in Transition Modelling

Georg Holtz[1], Joost Vervoort[2], Emile Chappin[3], Sharad Karmacharya[3]

[1]Institute of Environmental Systems Research, University of Osnabrueck

2Land Dynamics, Wageningen University and Research Centre

[3] Section Energy & Industry, Faculty of Technology, Policy and Management, Delft University of Technology

Abstract

If industrialized societies are to become truly sustainable, several societal subsystems, such as the transportation and power production systems need to change radically. This insight has stimulated the use of simulation models to study processes of system innovations - or 'transitions'. This article presents an appraisal of conceptual and methodological issues of studying transitions using computer simulation models. It relates the current state of empirical and conceptual work on transitions to insights from modelling of complex systems. For this, it explicates intrinsic characteristics of transitions and the knowledge base available to study them and discusses implicated challenges and opportunities for model application. It is concluded that parsimonious, transparent models aiming at conceptual advancement are currently the most promising route forward.

Keywords: Transition; System Innovation; Model; Modelling; Simulation; Societal Subsystem; Concepts; Methodology; Social Simulation; Complex Systems; Complexity;

1. Introduction

It has become more and more apparent that achieving sustainability of industrialized societies requires fundamental changes in different societal subsystems, such as the agricultural, transportation and power production systems. This insight has stimulated research aiming at understanding dynamics of systemic innovations in such systems as well as studies on the role of management and governance. Apart from receiving increasing attention in disciplinary fields, such "transitions" –like a transition to a carbon-neutral energy system or a transition to sustainable food production - have been investigated through integrated, interdisciplinary research. This has led to the emergence of an own field, "transition" research. Proponents of this study area highlight that the processes investigated encompass co-evolutionary and mutually reinforcing processes in the economic, technological, institutional[1] and socio-cultural domain and thus have to be studied from a truly interdisciplinary perspective (e.g. Elzen and Wieczorek, 2005; Geels, 2002; Konrad, Truffer and Voß, 2003; Pahl-Wostl, 2007; Rotmans et al., 2001; Weaver and Rotmans, 2006). However, taking such a perspective comes at the 'cost' of conceptual and methodological challenges. This becomes especially apparent when utilising formal methods such as simulation models. Simulation models have played a minor role in transition research up to now. However, simulation models are potentially useful tools to inform and guide formulation of concepts and theories, to bridge theory and practice; and also to support endeavours aiming at influencing the dynamics of transitions[2]. Recently, researchers have started to address questions of transition research using computer models (Bergman et al., 2008; Chappin, 2006; Chappin and Dijkema, 2007; Chappin, Dijkema and de Vries, 2009; Chiong Meza and Dijkema, 2008; de Haan, 2008; Holtz, 2006; 2008; Kohler et al., in Press; Schilperoord, Rotmans and Bergman, 2008; Timmermans, de Haan and Squazzoni, 2008; Timmermans, 2008; Whitmarsh and Nykvist (2008); Weisbuch, Buskens and Vuong, 2008; Yücel and Chiong Meza, 2008). This newly emerging field is characterized by diverse approaches in terms of model objectives, methods used as well as level of abstraction adopted. This is not too astonishing since researchers from various backgrounds are involved. Their approaches to the topic reflect that the social sciences are fragmented in a diversity of approaches and schools and that the integration of the social and the natural sciences is still in its infancy.

This article presents an appraisal of conceptual and methodological issues in transition modelling through relating the current state of empirical and conceptual work on transitions to insights from modelling of complex systems. It explicates the vast scope of transitions, the inherent complexity and uncertainty and the underdeveloped knowledge base. This serves to identify challenges and opportunities for transition modelling and to derive recommendations and methodological

[1] We understand "institutions" as sets of formal and informal rules of the game (Schneberg and Clemens, 2006).
[2] So-called transition management (cf. Rotmans et al., 2001).

conclusions. Doing so, this paper provides a possibility for reflection and facilitates discussions that may help making transition modelling a fruitful branch of transition research. Although this article takes a modeller's perspective, most of the presented holds for any (formal) interdisciplinary conceptualization and representation of system innovation processes such as transitions to sustainability.

This article is structured as follows: section 2 gives an outline on transitions as framed in this article. Section 3 explicates challenges and opportunities for model building arising from the nature of the process investigated and from the limitations in knowledge that can be drawn upon. Section 4 draws methodological conclusions on modelling in the field of transition research. Section 5 summarizes the main findings.

2. An outline on transitions

Research on transitions has developed in partly independent strands, applying a diversity of labels like system innovation, socio-technical transition, societal transition, industrial transformation and technological transition. Rotmans, Kemp and Van Asselt (2001) shortly define a societal transition as

"a gradual, continuous process of structural change within a society or culture".

Geels (2002) is more descriptive stating that

"(t)echnological transitions (TT) are defined as major technological transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled. TT do not only involve technological changes, but also changes in elements such as user practices, regulation, industrial networks, infrastructure, and symbolic meaning."

Other definitions have been proposed later on and by other authors. Nowadays, a joint definition and description of transitions is still lacking. We discuss this in section 3.4, where we focus on epistemic uncertainty.

The main motivation of the growing transition research community is concerns about future transitions to sustainability. However, as a means to develop a knowledge base on the dynamics of transitions and to enhance our understanding of such processes, retrospective studies have been conducted. For the sake of illustrating the topic of transitions and to introduce some fundamental concepts, we briefly present an example of such a retrospective study: the transition from sailing ship to steam ship in the time period from 1780-1900 as described by Geels (cf. Geels, 2002 for a detailed description). Following Geels work, we introduce the multi-level perspective which is currently the dominant framework of transition research (Geels, 2002; 2005b; Rotmans et al., 2001). Three different levels are identified: in the main focus resides the "regime", a pattern of actors, practices and rules representing the dominant way of providing functionality. For instance, the shipping regime around 1780 included two types of ship-owners, namely chartered companies and captain ship owners, and sailing ships with large cargo-holding capacities whose design was encouraged, among other factors, by guaranteed prices and government regulation. It was further characterised by a dependency on wind and currents and mail as crucial means for communication. In the multi-level perspective, encompassing system(s) guiding and bounding regime development are represented by the "landscape" level. In the shipping example, this comprises e.g. emigration waves and changing regulations regarding colonial trade. "Niches" constitute deviations from the dominant regime pattern, forming alternatives to the regime. An initial market niches was using steam ships for passenger transport on inland waterways.

The overall dynamics of transitions is argued to roughly resemble an "S-form" pattern (slow change – fast change – slow change): they start from a relatively stable regime with alternatives forming in certain niches. Problems within the dominant regime itself or pressure from the landscape level open up the opportunity for alternatives to challenge the dominant regime. The regime loosens and after a phase of several connected, mutually influencing changes, a new regime emerges, forming a new, stable system.

The development of the steam ship regime out of its initial niche(s) was characterised by consecutive conquering of different market segments, which went hand in hand with technological developments. Steam ships were first utilised on short distances and with little freight (e.g. inland passenger transport, mail), their utilisation and further development being stimulated e.g. by mail subsidies. Technological advancements like an iron hull and screw propulsion enabled usage of steam ships in further existing and new emerging market segments like long-range passenger transport (induced by emigration waves, a landscape development) and finally also heavy freight transport, thereby by and by replacing sailing ships. The transition from the sailing ship regime to the steam ship regime was first of all a change in technology (steam ships replace sailing ships). However, it incorporated many other changes influencing and being influenced by technological change, for example establishment of new actor groups like professional ship owners or insurance companies; or changes in institutions like mail subsidies and fixed schedules for departure and arrival of ships (which only became possible through steam ships' relative independence from winds and currents).

3. Challenges and opportunities for the use of computer simulation models in transition research

Computer simulation models are potentially useful tools to enhance understanding of the diverse and complex interactions of so many actors, elements and processes that constitute a transition. In this article we understand a "transition model" as a model aiming at explaining macro level changes during a transition as emergent outcome of underlying mechanisms on lower levels (Timmermans, de Haan and Squazzoni, 2008). In this section we explicate challenges and opportunities for building such models arising from the properties of the processes analysed and from the limitations of existing knowledge. This appraisal provides a (non-exhaustive) overview on issues relevant for conceptualizing and investigating transitions.

3.1 The vast scope of transitions

A major challenge regarding the analysis, understanding and modelling of transitions arises from the required interdisciplinary view comprising institutional, technical, economic, cognitive and social elements. The following explicates the vast scope of transitions along the diversity of factors, levels and actors involved (cf. Elzen and Wieczorek, 2005).

A wide range of factors

Transitions are often framed around change of a technological artefact used to meet a human need (e.g. Geels, 2005a). Change in such an artefact (e.g. from sailing ship to steam ship) is accompanied by changes on the production side; involving cognitive aspects like problem framing and heuristics applied by engineers searching for innovative solutions, economic aspects like market competition, investment decisions and strategies of firms as well as integration in existing structures of production networks. It is also accompanied by changes on the user side like application in different market niches and use contexts, changing user preferences and routines or social construction of meaning of artefacts. Further, institutional aspects are involved like laws and regulations, existence of insurances or modes of ownership.

Multiple, connected levels

The arena for transitions in societal subsystems is not confined to a single scale, whether of time, space, power or other classifications. While natural systems operate on connected levels stratified on scales of time and space, humans, because of their capacity for foresight, and the reach of their technological innovations, have loosened themselves from these stratifications to a certain extent (Westley et al., 2002). The connectedness of functional levels in human-dominated systems, and the potential for sudden cross-level discontinuities is exacerbated by this human characteristic. Because transition research focuses on just this capacity for innovation and fundamental change, a multi-level perspective in terms of space (e.g. local, regional, global), time (e.g. ecological cycles, political cycles, life-time of infrastructure and products, innovation rates) and other scales is vital.

A diversity of actors

Within this dynamic multi-level environment that is connected to so many economic, socio-cultural and ecological aspects, a large group of actors, heterogeneous in terms of perspective, influence, organization and visibility is bound to be connected to any transition process, ranging from governments and multinationals to special interest groups and grass-roots NGO’s. Furthermore, the stakes of these actors in the process might change over time, and actors might disappear and appear during the transition.

Challenges and opportunities arising from the vast scope of transitions

Transitions are driven by and have consequences for many factors and actors located on multiple levels as outlined above. These aspects are not, in reality, truly separable when it comes to broad changes. However, the science that has studied them is traditionally divided across disciplines. Economics, sociology, ecology and their respective subdisciplines all maintain different worldviews and basic presumptions. Work on discourses (Williams and Matheny, 1995, Dryzek, 1997) has shown that these discipline-based presumptions are very ingrained, and often unacknowledged, like different accents in a language (Pritchard and Sanderson, 2002). Information communicated through a different discourse will be filtered and fitted to the perspective of the receiver to some degree. This way, what is seen as key information by one discipline could be ignored by another. Because of the difficulties of communication between discourses, much so-called multidisciplinary work results in misinterpreted messages. This is also a challenge for scientists that aim at interdisciplinarity in their own work. Efforts to include some understanding of system elements covered by different disciplines often still end up as caricatures compared to the work on one's own field of expertise. Formulated strongly, modellers simply require something to fill in the "environment" box in their economic model, "people" in their ecological model, and so on (Holling, 2002).

To overcome the challenge of gaining from very different types of knowledge, awareness of the potential for missed information when one ventures beyond familiar ground, and recognizing one's own discourse, or "set of glasses" is essential. Once the pitfalls of multidisciplinary work are recognized and acknowledged, models, which provide a common "language", have the potential to bridge the conceptual divide between disciplines. Model "languages" like mathematics, system dynamics diagrams or computer code are more precise than common language and leave less room for misinterpretations. In that way models provide a means of communication and collaboration supporting scientific discussions.

3.2 The inherent complexity of transitions

Transitions are processes of change in complex systems. Various definitions, measurements and explanations of "complexity" exist (cf. e.g. Cowan, Pines and Meltzer, 1994; Gallagher and Appenzeller, 1999). In the following discussion we mean systems constituting "wholes" due to emergent properties rooted in non-linear interdependencies of system elements. We briefly discuss some essentials of complexity and outline implications for model building.

Complexity in a nutshell

Systems consist of interdependent elements. Through interdependencies, signals like change of an element's internal state cut across this element and influence connected elements. The respective potential adaptation of affected elements might propagate through the system and also feed back to the original source. In that way a signal potentially provokes a cascade of interacting adaptation responses. In a system of dynamic, interdependent elements, elements change simultaneously while continuously mutually influencing each others development. Consequently, elements behave in a different way as they would do in isolation but cause and effect can not be separated clearly. We use the term “co-dynamics” to refer to such patterns of mutual influences and adaptations (cf. Winder, McIntosh and Jeffrey, 2005). Complexity arises from the non-linear coupling of interdependent elements. Non-linearities reflect processes such as growth phenomena, diffusion processes, thresholds, learning, time-delays and saturation phenomena. Non-linear interdependencies bring forth that small causes might have big effects on connected elements or vice versa. The coupling of multiple non-linear processes in a complex system exaggerates these effects making system response potentially highly sensitive to the state of the system and the specificities of a signal.

Consequently, complex systems exhibit surprising and unexpected pattern in their dynamics and their structure. These patterns emerge from co-dynamcis and non-linear coupling of system elements and can not be explained from the properties of single system elements nor by a mere aggregation of properties of system's parts. They are irreducible to single elements or their properties. Recognizing and understanding emergent properties constitutes a vital part of the understanding of complex systems.

Challenges and opportunities arising from complexity

Mirroring the effect in real complex systems, the specific form of model elements and interdependencies influences the resulting co-dynamics of the modelled system and determines emergent properties governing the modelled system. Consequently, results obtained by computer models of complex systems are sensitive to conceptual and implementational design decisions. A major challenge for researchers in general and for modellers in particular is hence to correctly capture those elements and non-linear interdependencies that govern system behaviour.

This is not a trivial task. Empirical observations usually provide evidence on the dynamics of one or several variables (e.g. adoption rates of a new technology). However, the system structure generating these observed dynamics is not easily identified. No general methodology to extract the form of underlying non-linear interdependencies exists. As Holland (1996) puts it: “Non-linearities mean that our most useful tools for generalizing observation into theory – trend analysis, determination of equilibria, sample means, and so on – are badly blunted.” Difficulties in specifying non-linearities lead to the situation that the understanding of the structure of a system generating observed behaviour of some variables is often incomplete.

This outlines a situation in which computer models have been fruitfully applied to enhance the understanding of complex systems. Computer models are excellent tools to explore the possible configurations of complex systems and to draw conclusions on the relation of system structure and corresponding dynamics. Computer models can aid the search for most relevant elements and processes governing system behaviour. The field of ecosystem modelling shows that comparably simple models can be built that capture relevant dynamics of complex systems (Gunderson and Holling, 2002).

3.3 Variability uncertainty

An extensive literature exists on uncertainty in model building and many different frameworks and concepts have been proposed (e.g. Brugnach and Pahl-Wostl, 2007; Refsgaard et al., 2007; Walker et al., 2003). Walker et al. (2003) provides a synthesis of many contributions on uncertainty in model-based decision support. There they define uncertainty in a broad sense as *"any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" (p. 5).* Obviously, uncertainty is pervasive in transition modelling. In this article, we do not aim at providing a specific uncertainty classification for transition modelling but merely discuss some aspects of uncertainty which we consider especially relevant in this field. In terms of the framework proposed by Walker et al. we use the nature of uncertainty - variability uncertainty and epistemic uncertainty - to structure this discussion. This subsection first elaborates on variability uncertainty and epistemic uncertainty is discussed in the next subsection (3.4).

Variability uncertainty refers to "inherent uncertainty or randomness induced by variation associated with external input data, input functions, parameters, and certain model structures." (Walker et al., 2003, p.13). One source of variability existing in socio-technical systems arises from the creation of innovations (e.g. technological innovations, innovative institutions). If and when such innovations enter the system, how they manifest and what kind of effects they have on the system cannot precisely be known in advance. Further, systems in transition are not isolated but exposed to influences from the system environment. Such influences include changes of various kinds on the landscape level, like the Chernobyl disaster, an economic crisis or the introduction of high-level institutions like the European Water Framework Directive. A regime is also exposed to influences from connected regimes (cf. Geels, 2007; Konrad, Truffer and Voß, 2003) like for instance the impact of agriculture on water management. Agriculture is a major user of water resources and a major polluter as well. Another source of variability is not related to unexpected events that "disturb" the smooth development of the system but is inherent in the system itself. The internal dynamics of regimes and niches generate branching points which enforce the choice of a future course. For instance, if a major player decides between rival technological designs pushing one design[3]; or a new legal law becoming more or less strict depending on the outcome of a political process. The choice of the respective actors is a kind of inherent variability potentially deciding about the future direction of an unstable system.

<u>Challenges and opportunities arising from variability uncertainty</u>

Concrete manifestations of variable elements are naturally unpredictable ex-ante. However, they might influence system development, especially if the system is path-dependent (Arthur, 1994). Path-dependency is often discussed with respect to incumbent regimes where path-dependency is argued to

[3] For example, in the transition in Swiss food production, the strategic decision of Coop to introduce a broad range of organic food products stimulated expansion of this niche compared to the alternative designs of Integrated Production and Integrated Production Plus. The expansion of the niche stimulated further programmes of competing food retailers (Belz, 2004).

stabilize this regime (Dosi et al., 1988; Nelson and Winter, 1977). However, in the dynamic and unstable phase of a transition, path-dependency also means that continuously future developments are shaped and channelled through current actions. Consider the following example: the decisions of house builders to install solar cells are influenced by the amount of subsidies granted. If subsidy schemes change, say in a disputed decision more subsidies are provided, demand will increase. Firms supplying solar cells will react on changes in demand. Potentially a major player of the incumbent energy regime decides to enter the market. In reaction to increasing demand, production will increase what might stimulate further research possibly leading to a technological break-through or in contrast to stagnation of learning curves and loss of faith in potentials of a technology. The development of the market and estimates of technological development as well as lobbying activities of actors involved will influence the decision made in the political arena reviewing and adapting the subsidy scheme. This simplified example illustrates how system trajectories branch out through "random" manifestations of variable aspects (subsidy scheme, major player entering the market, break-through or stagnation in technological development) and corresponding implications on future developments. In transitions, many variable aspects are involved, creating a vast tree of possible pathways.

Models can be used to explore the space of possible developments arising from the interplay of multiple sources of variability uncertainty. They can help to identify development branches which encompass most promising states as well as those branches that contain most undesired developments. The challenge for model building resides in mapping the space of simulations specifically enough to allow conclusions on key processes and events. Scenarios can help to explore and structure the space of simulation results of a model. Scenarios predefine the development of some aspects of the system or its boundary conditions in a coherent and reasonable way. Doing so, scenarios restrict simulation runs to certain parts of the space of simulation results and facilitate an understanding of the implications of the assumptions embodied in the definition of the scenario.

3.4 Epistemic uncertainty

The challenges discussed up to now are intrinsic in the topic of transitions. In this section we discuss challenges that relate to the knowledge base of transition research.

Conceptual vagueness

The concept of "transition" has been applied to processes in diverse sectors like for instance the transition from sailing ship to steam ship (Geels, 2002), a transition in Dutch water management (Van der Brugge, Rotmans and Loorbach, 2005) and the breakthrough of rock'n roll (Geels, 2007). Different author use slightly varying terminology (e.g. "socio-technical transition", "societal transition" or simply "transition") and propose varying lists of factors or domains incorporated (technology, economics, cultures, routines, infrastructure, rules, institutions, actor groups, networks, environment, paradigm, etc.). As Squazzoni puts it: "*(E)ach branch of the literature on transitions seems to be inclined towards producing its own labels, concepts and models, with the consequence* *that generalisation and theoretical cumulativeness (…) are difficult to achieve."* (Squazzoni, 2008, p.18f). The shared characteristics that classify a process as "transition" commonly agreed upon remain on a very general and qualitative level as described in section 2: the metaphor of an S-form, the interaction of multiple levels, and transitions being processes involving multiple actors and factors. Also for other basic concepts of transition research, like the notion of regime, currently no shared exact definition exists (cf. Holtz, Brugnach and Pahl-Wostl, 2008).

Some work to identify more specific concepts is currently conducted but not yet integrated in the shared body of knowledge as defining characteristics of transitions: Rotmans et al. (2001), van der Brugge, Rotmans and Loorbach (2005) and others use the concept of four "phases" of transitions. Smith, Stirling and Berkhout (2005) suggest four "transitions contexts" that lead to different transition dynamics while Geels and Schot (2007) propose that different pattern of timing and nature of multi-level interactions generate different transition dynamics. Haxeltine et al. (2008) propose a conceptual framework for transition modelling that includes definitions of basic concepts as well as a set of more specific mechanisms proposed to underlie different transition paths.

Challenges and opportunities arising from conceptual vagueness

The concepts agreed upon up to now by transition researchers (S-Form, multi-level, many actors and factors) are very general and provide little guidance for the evaluation of models. Many conceptually completely different models are e.g. able to reproduce dynamics that resemble an S-form (cf. Bergman et al., 2008 and Yücel and Chiong Meza, 2008). More specific concepts rendering more precisely classes and characteristics of transition (sub-) processes are needed to relate transition models to empirical work and theory (Haxeltine et al., 2008). The framework developed by Haxeltine, Whitmarsh et al. aims at providing a bridge between theory, empirical analysis and model building (Haxeltine et al., 2008). Developing, discussing and agreeing on such a framework (or a set of acknowledged frameworks) are important next steps for transition research. Models can aid this process. They can be used to explore the interactions and possible dynamic behaviours of structures and sub-processes proposed in such frameworks, doing so informing the debate on framework development.

Understanding socio-technical systems

In several fields like physics, weather forecast, complex chemistry or ecology, models proved to be useful tools to enhance understanding and management of complex systems. Transitions differ from these fields in the sense that change in socio-technical systems is at the heart of a transition. Various actor groups are involved in transitions; like firms, consumers, associations, administration, politicians etc. A societal subsystem is constituted by the interactions of such actor groups[4]; and a transition -

[4] For instance, in case of nowadays car-based mobility in industrialised countries like Germany or the Netherlands, car manufacturers sell cars while some governance ministry deals with regulations regarding environmental standards of cars and another one is responsible for building and maintaining streets. Oil-companies provide fuel, repair shops provide necessary service and financial institutions offer different kinds of insurances. The consumers privately owning cars follow the practice of "all-times for all-purpose" usage.

change in a societal subsystem - includes change in the behaviour, interaction and composition of these actor groups. Therefore change in human behaviour and social relationships must be embraced by transition researchers and transition modellers. The formally most advanced of the social sciences is economics. Economic aspects are important are transitions and may constitute a backbone of transition models. However, one of the pillars of transition research is that economic aspects alone are insufficient to understand e.g. resistance of regimes to change but that inter alia institutions and power relations have to be considered as well.

Challenges and opportunities regarding the representation of socio-technical systems

Several parts of socio-technical systems, especially governance systems are not (easily) accessible to modelling. According to Mayntz (2004) our theoretical understanding of processes whose dynamics are strongly influenced through specific constellations of corporate actors and which involve a variety of structural and institutional features is limited. That means theories and concepts being usable as base for modelling governance related parts of socio-technical systems are mostly lacking. Such a lack of understanding is rooted in the more fundamental weakness of an absence of a unified view on human behaviour. Several acknowledged, but sometimes non-compatible concepts explaining individual human behaviour have been developed by economists, sociologists, psychologists and others. However, which concept is most appropriate in which context is often not known or otherwise disputed. Another issue of hot debated is the interdependency of human agency and social structure. While some scholars, especially economists, highlight the importance of individuals (interacting in a market), others emphasize the role of social structures like norms and routines for understanding social systems. Although these views are not completely incompatible (cf. e.g. Giddens, 1984), how individual behaviour is influenced through social structures and how social structure in turn is shaped through individuals' behaviour is a core research issue in the social sciences of which understanding is limited. In sum, in contrast to most fields in which models have been fruitfully applied to deal with complex systems, when modelling social and socio-technical systems, the fundamental underlying laws are not known (if such laws exist at all in the social sphere). Further, with the exception of economics, existing concepts are rarely elaborated in a formal way easily transferable into a model. Simulation is still a young field in the social sciences which still needs progress in methodology and standardization (Axelrod, 2003). Researchers in the interdisciplinary field hence face the challenge to select one specific model design potentially facing many different possibilities. However, which choice is made might be crucial for results (Hare and Pahl-Wostl, 2001). Still, models can be used to explore the relevance and respective consequences of varying assumptions about human behaviour. This might be useful to distinguish transition phases which are dominated by (social) structures from more instable phases in which human agency matters. This may e.g. help to refine our understanding about behavioural patterns which induce or block transitions.

3.5 Promising future routes in transition modelling

The discussions up to now have created a basis from which we can suggest future avenues for modelling to make a valuable contribution to transition research. Given the vast scope of transitions we have suggested models as means of communication and collaboration to bridge the conceptual divide between disciplines. The use of models with regards to that has been discussed elsewhere (Rotmans, 1998, Lotze-Campen, 2008). We further have identified models as tools to explore the space of system trajectories created by variability uncertainty. However, the space of simulation results that can be explored in such an exercise is rooted in the structure of the model. To our knowledge little work has been done on comparing the variety of model results rooted in variability uncertainty (parameters, random numbers) to such rooted in model structure (for an exception see Hare and Pahl-Wostl, 2001). However, it can be argued that the model structure is a more fundamental aspect. Hence we presuppose a high level of confidence in model structure being a prerequisite for modelling exercises exploring the space of system trajectories created by variability uncertainty. Our discussion of complexity and epistemic uncertainty shows that we do not have such a high level of confidence in the structure of transition models. From our perspective, addressing challenges arising from complexity and epistemic uncertainty are most urgent for transition research and provide most promising routes for transition modelling.

These challenges comprise to develop and agree on defining characteristics of transition processes, to identify and generalize elements and processes involved in transitions and to improve our understanding about how they are interacting in a transition. The explanatory power of single models might be limited, due to the uncertainties involved. However, we are confident that a multitude of models and model variations can confirm and/or refine the current conceptual base significantly. This will be the case if several models point into the same direction. For example, Bergman et al. (2008) as well as Yucel and van Daalen (2008) both have modelled the transition from sailing ship to steam ship introduced in section 2. Although utilising very different frameworks as base for their respective models, both studies conclude that differentiated markets in combination with economies of scale and technological advancements were key aspects of this transition. Such consensus substantiates findings and makes the results more robust.

Further, and perhaps more importantly, model building is a fruitful way to structure knowledge. Formalizing concepts requires a stringency which helps identifying gaps in less formal descriptions. Model building helps to structure an issue, provides a base for discussions and potentially leads to a refined set of questions. Models are highly valuable as thinking tools.

4. Methodological conclusions

The previous section identified challenges and opportunities for transition modelling arising from intrinsic characteristics of transitions and from the knowledge base available to study them. We have suggested addressing challenges arising from complexity and epistemic uncertainty through using models to identify and generalize elements and processes involved in transitions as most promising route forward. Although we are optimistic about simulation models' power to contribute to a more profound fundament for transition research, in this section we argue that the vast scope of the topic in combination with its intrinsic complexity and the uncertainty involved constitute severe challenges to model building necessitating a well-balanced and deliberate modelling approach right from the beginning. We argue that the objectives of a model exercise play a key role in achieving a methodologically manageable model and suggest parsimonious models tailored to answer specific questions as the most promising modelling approach.

4.1 Transition models need to be tailored around well-defined objectives

Multiple model structures are reasonable

When building a conceptual model, the identification of relevant aspects relies on knowledge about factors determining the dynamics of one or several interesting dependent variable(s). The vast scope of transitions offers a multitude of elements and processes that could be considered relevant. As discussed in the section on epistemic uncertainty (section 3.4), no fundamental laws of social systems have been established by the social sciences, but a modeller has to make some subjective assumptions and/or choices among several alternatives proposed by different (and often rivalling) schools. Multiple model structures can be argued to be reasonable.

Substantial difficulties hinder corroboration of the superiority of a specific model structure. Potentially, several different models are able to reproduce the same set of stylized facts and/or data sets. This many-to-one relation is a well-known problem for identification of "correct" models of complex systems. The reason is, as Sterman (2000) puts it, that *"(t)he number of variables that might affect the system vastly overwhelms the data available to rule out alternative theories and competing interpretations"* (p. 25). When modelling complex systems, evaluation might show that a specific model is reasonable but can not prove invalidity of alternative model designs. This coexistence of explanations, known as equifinality (also called 'under-determination problem' or 'identification problem' (Windrum, Fagiolo and Moneta, 2007)), still pertains in modelling fields having a longer tradition than transition modelling, like modelling of environmental systems (Beven, 2002). The epistemic uncertainty in transition research allows for a broad range of reasonable model designs.

Parsimonious, transparent models can contribute to the knowledge base

If confidence in the model structure is low and it is not possible to prove the superiority of a specific model design, then, adhering to transparency of models seems to be a reasonable way forward. By "transparency" we refer to the possibility of relating simulation results to particular characteristics of the model structure and assumptions made; generating insights on how certain factor combinations result in specific dynamics. If models are transparent, insights can be abstracted from the specific model used to gain them. In this way, transparent models contribute significantly to the knowledge base on the modelled system(s).

We conclude from the discussions in section 3.2 that in the realm of complexity only parsimonious models are transparent. The co-dynamics and the effects of emergent properties in broad and complex models easily overrun the capabilities of the human mind to comprehend resulting dynamics. Hence only for parsimonious models we are able to distinguish characteristics of a system and its dynamics from model artefacts and can draw conclusions on the relation between simulation results and inevitable uncertainties in model design.

Clear and specific objectives are crucial

Given the vast scope and complexity of transitions, any parsimonious model necessarily must neglect or considerably simplify some aspects of the modelled system. Regarding the complex interdependency of many relevant actors, factors, scales and processes, parsimonious models hence do not reflect transition dynamics completely and seem inappropriate to capture the full complexity and scope of transitions. A modeller has to choose between confining a model to certain parts of the overall transition (as an example see Holtz, 2008), or to strongly simplify matters (e.g. de Haan, 2008). Consequently, if transparency is aimed at, there is no universal transition model. This view reflects a general insight from complexity studies: complex systems must be modelled differently to answer different sets of questions. The objectives of the modelling exercise define the view on the system taken; therefore clear and specific objectives are crucial for successful model building. Sterman: "The art of model building is knowing what to cut out, and the purpose of the model acts as the logical knife" (Sterman, 2000, p. 89). Sterman concludes: "Always model a problem. Never model a system." (p. 90).

A resulting major challenge for transition modelling is identifying and clearly specifying objectives which are on the one hand contributing to the body of knowledge of transition research while at the same time defining a manageable modelling exercise allowing transparency of the resulting model. In rather general terms we have identified the most pressing objectives for transition modelling as to identify and generalize elements and processes involved in transitions and to improve our understanding about how they are interacting in a transition. This overall agenda may serve as a guideline but has to be rendered more precisely to define a specific modelling exercise.

We have considered models tailored to answer specific questions the most fruitful approach for transition modelling and have suggested building parsimonious models that strongly reduce the complexity of the real system. When doing so, it is important for the interpretation of model results to also have in mind what is neglected or oversimplified by the model and which alternative modelling routes could have been taken. Results have to be put into context and compared to other works to fully understand the consequences of choices made in the model design. This point is especially relevant because transition modelling is a new research field and scientists working on the topic start from their perspective, being accustomed to their "glasses", discourses and tools. They might therefore tend to interpret transitions from their current viewpoints, utilising concepts and methods they are familiar with. It is important to embrace equifinality and to remember that no single model can claim to constitute the only valid characterisation of a given problem situation. To overcome the divide between disciplines and to develop a joint knowledge base an open-minded community of transition modellers, willing to relate and compare models originating from diverse backgrounds is essential.

5. Conclusions

This paper presents an appraisal of conceptual and methodological issues in transition modelling. We have explicated the vast scope of transitions, their complexity and the relevance of uncertainty and identified challenges and opportunities for model building. Given the vast scope of transitions we have suggested models as means of communication and collaboration to bridge the conceptual divide between disciplines. We further have identified models as tools to explore the space of system trajectories created by variability uncertainty. However, given a lack of accordance regarding the structure of current transition models, addressing challenges arising from complexity and epistemic uncertainty are most urgent and currently provide most promising future routes for transition modelling. Model building can help identify and generalise elements and processes involved in transitions and improve our understanding about their respective roles. This can contribute to the development of a shared terminology and of a set of shared basic definitions, an issue which still requires a lot of work although progress has been already made recently.

We argue that given the combination of challenges identified in this article, parsimonious, transparent models, designed to achieve specific objectives are most promising to enhance the knowledge base of transition research. Objectives need to be well defined to guide design of models. In rather general terms we have identified the most pressing objectives for transition modelling as to identify and generalize elements and processes involved in transitions and to improve our understanding about how they are interacting in a transition. This overall agenda may serve as a guideline but has to be rendered more precisely when defining a specific modelling exercise.

Due to the epistemic uncertainty associated with the current state of understanding of transitions, results of individual modelling exercises have to be put into context and compared to other works to fully understand the consequences of choices made in the model design. Acknowledging and embracing equifinality is of major importance in the field of transition modelling to overcome the divide between disciplines and to develop a joint knowledge base.

Transition modellers are undertaking a challenging endeavour which is only just starting. Based on our appraisal presented in this article we propose models not to be considered being silver bullets solving all problems of transition research. But they can be valuable tools contributing to the enhancement of the knowledge base of the field.

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Paper 2: Current state

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Transition modelling – current state and future routes

Georg Holtz

Institute of Environmental Systems Research, University of Osnabrueck

Georg.Holtz@usf.uos.de

Abstract

A transition model explains long-term fundamental change in a societal subsystem as emergent outcome of an underlying mechanism (Squazzoni, 2008a). This article discusses to which extent and in which way such a generative mechanism can simplify the real process. A brief review of recent transition models reveals substantial differences regarding assumed essential entities and interactions. A subsequent conceptual discussion concludes that the reviewed models fall short in capturing essential micro-macro interactions and are over- simplified compared to the richness of entities and interactions identified in conceptual and empirical works. It is then argued that increasing the complexity of models is nevertheless not a reasonable way ahead. Instead it is proposed to make better use of building blocks of an intermediate level of complexity – e.g. timing and kind of multi-level interactions (Geels and Schot, 2007). Two types of modelling exercises are suggested.

Keywords: Transition; System Innovation; Model; Simulation

1. Introduction

Research on transitions has grown into an own field. It deals with long-term fundamental change in societal subsystems, such like a transition to a carbon-neutral energy system or a transition to sustainable food production and approaches the topic from an interdisciplinary perspective, building on concepts from a variety of fields like complexity theory, innovation studies, governance studies and evolutionary economics. Transition researchers have mostly presented qualitative studies utilizing high-level frameworks to structure narrative descriptions (e.g. Elzen, Geels and Green, 2004; Geels, 2005a; Rotmans, Kemp and van Asselt, 2001). But recently, researchers have also started to address questions of transition research using computer models (e.g. Timmermans and de Haan, 2008; Bergman et al., 2008). Computer models provide an analytical approach that, being precise and stringent and providing a means to study emergent properties, can complement previous studies and can address some of their short-comings. This article presents an appraisal of some conceptual and methodological issues in such transition modelling. As such it complements Squazzoni (2008a) and

Timmermans, de Haan and Squazzoni (2008). Those articles relate the emerging transition modelling field to other (disciplinary) approaches dealing with structural change, discuss why modelling can advance transition research and suggest what actually constitutes a “transition model” – an explanation of macro level changes as emergent outcome of an underlying generative mechanism[1]. Such a transition model needs to find a balance in the tension between the overall agenda of transition research, which argues that due to their complexity those processes can not simply be explained through reducing them to something very much simpler, and the purpose of modelling which is actually to reduce complexity through highlighting the essential aspects of a process and excluding marginal influences. The crucial question is to which extent and in which way a model of a transition can simplify the real process without loosing explanatory power. This article approaches this question as follows: section 2 gives an introduction to transition research and recapitulates the potential benefits of transition modelling. Section 3 reviews recent transition models and analyses similarities and differences in those models. This is complemented by a conceptual discussion, which provides some additional insights on properties of generative mechanisms, especially on the relevance of micro-macro interactions for understanding transitions. It is argued that hitherto models fall short in capturing essential micro-macro interactions. Section 4 gives an argument that building more complex models is nevertheless not a reasonable way ahead and that building a transition model that aims to provide a generative mechanism fully explaining a transition is (currently) over-ambitious. Based on this, alternative future routes drawing more explicitly on available building blocks of explanation of an intermediate level of complexity are suggested. The last section summarizes and draws overall conclusions.

2. Transition research and transition modelling

2.1 A brief introduction to transition research

Transition research has investigated a diverse set of processes, like for instance the transition from sailing ship to steam ship (Geels, 2002), a transition towards a sustainable energy system (Rotmans et al., 2001), a transition in Dutch water management (Van der Brugge, Rotmans and Loorbach, 2005), the transformation of utility sectors (Konrad, Truffer and Voß, 2008) and the breakthrough of rock’n roll (Geels, 2007). What those processes have in common, and what is thus the unifying perspective of various transition studies, is that those processes can be perceived as coherent long-term change process arising from co-evolutionary and mutually reinforcing (sub-) processes on multiple levels and in various domains (economic, technological, institutional, socio-cultural). Transition research is a

[1] A “generative mechanism” refers to a constellation of entities (e.g. actors, technologies, institutions) and interactions leading to a specific type of phenomenon (e.g. a spatial or dynamic pattern). See section 3.1.

young field which has developed in partly independent strands, applying a diversity of labels like *system innovation*, *socio-technical transition*, *societal transition*, *industrial transformation* and *technological transition* and which still struggles with establishing its conceptual basis. Different authors use slightly varying terminology and propose varying lists of factors incorporated in transitions (technology, economics, cultures, routines, infrastructure, rules, institutions, actor groups, networks, environment, paradigm, etc.). A joint definition and description of transitions is still lacking. As Squazzoni puts it: "*(E)ach branch of the literature on transitions seems to be inclined towards producing its own labels, concepts and models, with the consequence that generalisation and theoretical cumulativeness (…) are difficult to achieve.*" (Squazzoni, 2008a, p.275). For the sake of this article no further definition is added, instead the labels "transition research" and "transition modelling" refer to those works that use those labels themselves and whose topic complies with those very general and qualitative characteristics that are commonly agreed upon as classifying a process as "transition": the metaphor of an S-formed dynamics (slow pre-development - fast self-reinforcing changes - stabilization), the interplay of developments on multiple levels and the interdependency and co-evolution of a range of actors and factors from various domains in generating what can be perceived as coherent long-term change process.

It is useful for further illustrating the topic and for providing a basis for discussions in subsequent sections to briefly introduce the multi-level perspective (MLP), a framework nowadays widely used to describe transitions (e.g. Geels, 2005a; Geels, 2005b; Rotmans, Kemp and van Asselt, 2001; Genus and Coles, 2008). In this framework, three different levels are identified: in the main focus resides the "regime", a pattern of actors, practices and rules representing the dominant way of providing functionality. For instance, in case of nowadays land-based mobility in industrialized countries, the regime can be sketched around the internal-combustion engine driven car: manufacturers sell cars while some governance ministry deals with regulations regarding environmental standards of cars and another one is responsible for building and maintaining streets. Oil-companies provide fuel, repair shops provide necessary service and financial institutions offer different kinds of insurances. The consumers privately owning cars follow the practice of "all-times for all-purpose" usage. The "landscape" level represents the encompassing system(s) guiding and bounding regime development. In the mobility example, this refers to things like (political reactions to) climate change, depletion of oil resources, a (still) increasing need for mobility and changes in environmental awareness. On the lowest level, "niches" constitute alternatives to the regime. Niches may emerge around novel vehicles and fuels (e.g. hydrogen driven or electric car) or from shifts in institutions (e.g. car-sharing) (cf. Whitmarsh and Nykvist, 2008).

The "classical" dynamic pattern of a transition would then start from a relatively stable regime with alternatives forming in certain niches. Problems within the dominant regime itself or pressure from the landscape level open up the opportunity for alternatives to challenge the dominant regime. The regime loosens and after a phase of several connected, mutually influencing changes, a new regime emerges, forming a new, stable system. However, it must be noted, that other transition patterns and pathways have been identified (Geels and Schot, 2007; Konrad, Truffer and Voß, 2008; Smith, Stirling and Berkhout, 2005) and it should be stressed that although historical transitions are naturally seen in the light of the starting point and the end-state, this end-state of a transition is not pre-determined from the onset.

2.2 The benefits of modelling transitions

Historical transitions have usually been "explained" through some form of narratives guided by a framework like the multi-level framework. This gives an in-depth intuitive understanding of the respective case. However, *"the analysis is powerful at a descriptive level but low at an analytical level"* (Squazzoni, 2008a, p. 275) what makes it difficult to derive generalizations. Further, such narrative descriptions have a hard time *explaining* (rather than only describing) the generation of macro-level changes since the complex nature of the systems involved provides a barrier to comprehend the appearance of emergent macro dynamics.

Computer simulation models can address these short-comings. On the one hand model building requires an analytical view on a system - stringency, clear definitions and explication of what is taken into account as explaining the observed phenomenon. This makes descriptions precise enough to be testable and generalizable across cases. On the other hand, models are able to close the micro-macro gap through generating dynamics based on interactions of model elements, doing so putting the implemented generative mechanism to a test. Squazzoni argues that the *"main challenge of transition studies is to work with analytical models that allow us to map the micro-macro generative mechanisms that can explain the emergence of transitions, at the same time making traceable the alignment of intersectoral changes that characterizes each societal transition."* (Squazzoni, 2008a, p.267). Following this proposition regarding the role of modelling in transition research, in this article a "transition model" refers to a model explaining a transition as emergent outcome of underlying mechanisms (see also Timmermans, de Haan and Squazzoni, 2008).

3. Considerations on the structure of generative mechanisms

3.1 Explanations based on mechanisms

Using this definition of a transition model as explaining a transition through providing a generative mechanism suggests briefly discussing both key notions – "explanation" and "mechanism" - before going on. Roughly speaking, an "explanation" answers the why-question. Getting more precise, what actually constitutes an explanation is no so clear-cut in the social sciences (cf. the discussion of different kinds of explanation in Hedström 2008). In this article I consider an explanation complete if it provides a complete causal reconstruction of processes leading to the observed phenomenon (Coleman 1990; Mayntz 2004, 2009; Hedström 2008). Processes in social systems are driven by actors' activities. Therefore a complete explanation of a transition would require identifying the involved actors and explaining their activities in the context in which these activities unfold (which comprises e.g. institutions, existing infrastructure, technological artefacts). Besides identifying involved entities[2], a further important step of providing an explanation is to specify how a macro phenomenon arises from entities' (recurrent) interactions, i.e. to capture the emergence of the macro phenomenon. Both steps together constitute a generative mechanism (Hedström 2008, Squazzoni 2008a, Mayntz 2004): a constellation of entities (e.g. actors, technologies, institutions) and interactions leading to a specific type of phenomenon (e.g. a spatial or dynamic pattern).

Considering the involvement of many entities in transitions (see section 3.3), it may not always be convenient to provide an explanation disaggregated to the level of actors' activities. Indeed transitions are often described in terms of interactions of higher level structures such as regimes and niches. Given the requirements for an explanation defined above, such descriptions may provide explanations for transitions, but only if the used aggregated elements and processes can (in principle) be explained through disaggregating them to the entity level.

3.2 Mechanisms in recent models

In order to show that transition modelling can become a fruitful branch of transition research, the added value of transition models needs to be demonstrated. With respect to the role of models in transition research suggested above, this would mean that models should enhance our understanding of the mechanisms underlying transitions. This section argues that current models have yet had limited success with that[3]. We have a suite of models potentially able to explain something about transitions, but it is (partly) unclear what exactly can be concluded from them and what can be transferred back to empirical and conceptual work. This does not mean to be a harsh critique but the author is well aware of the exploratory character of those first transition models and it needs to be underlined that those

[2] For sake of convenience, here and in the following “entity” is used as an umbrella to refer to actors, technologies, regulations, norms, infrastructure etc. on a micro-level of abstraction. “Element” is used as a more general term which comprises besides entities also macro-structures sometimes used in models, such as regimes and niches.

[3] It may be noted here that the main objectives of the models discussed are highly diverse (e.g. demonstrating usefulness of a method for transition modelling (Yücel and Chiong Meza 2008) or assessing the effect of alternative policies (Chappin et al. 2009)) and that those model exercises are modest and do not claim to provide definitive answers on what constitutes a generative mechanism for a transition. Anyway, for the purpose of this article it is most interesting what can be learned from these models with respect to generative mechanisms of transitions.

models provide a starting point which brings to the front a refined set of questions which can be fed into further modelling exercises. But in order to advance the field, it is useful to analyse weaknesses and to suggest future routes (see section 4). The discussion is based on a review of recent transition models: a special issue in CMOT (de Haan, 2008; Schilperoord, Rotmans and Bergman, 2008; Timmermans, 2008; Weisbuch, Buskens and Vuong, 2008; Yücel and Chiong Meza, 2008), a session on transition modelling at ESSA 2008 conference (Chiong Meza and Chappin, 2008; Holtz, 2008; Yücel and van Daalen, 2008) and recent related publications (Bergman et al., 2008; Köhler et al., 2009; Chappin, Dijkema and De Vries, 2009). Several publications (Bergman et al., 2008; Köhler et al., 2009; Schilperoord, Rotmans and Bergman, 2008) relate to the same model developed in the MATISSE project building on a framework developed by Haxeltine et al. (2008). Those models are sometimes summarized as "the MATISSE model" in the following discussions. Table 1 provides an overview of the reviewed models.

The reviewed models implement a variety of different essential entities and interactions. Although each model brings up an own approach, the following summarizes some clusters: some authors represent explicitly actors separate from a physical world (technology, infrastructure, nature) and/or rules/institutions and mostly assume diffusion processes, heterogeneity of preferences, increasing returns to scale and market mechanisms as drivers of change (Weisbuch, Buskens and Vuong, 2008; Yücel and van Daalen, 2008; Holtz, 2008; Chappin, Dijkema and De Vries, 2009). Actors are represented as having some (potentially dynamic) preferences and choosing among options (usually technologies), while the attributes of options change according to usage by actors. Institutions are fixed or change exogenously. Those exercises mostly focus on changing market shares of options as emergent outcome. Others model niches and regimes located and moving in some "practice space" and focus on their "power games" (the MATISSE model; de Haan, 2008). Niches' and regimes' strengths grow or diminish depending on internal dynamics of the respective entity and through resource input depending on the location in the practice space.

In most models dynamics unfold "mechanistically" through actions of myopic actors and hard-wired responses of technologies' attributes and environmental elements. Here, the MATISSE model is prominent regarding the consideration of reflexive and strategic behaviour. In this model, regimes and niches follow meta-strategies based on a perception of the overall macro-situation. For example, empowered niches follow a "predator" strategy, adapting their practices with the aim to take away support from the regime. Depending on the location of empowered niche and regime in the practices space this might entail very different actions. The model presented in Chappin, Dijkema and De Vries (2009), whose main actors are power producing companies, also considers some strategic elements through actors taking into consideration investments and decommissioning announced by competitors.

The broadness of the reviewed models in terms of different domains and levels considered is strongly varying. Roughly distinguishing approaches, it can be said that some exercises

Publications	Topic	Purpose	Conceptual / empirical basis	Main model elements	Method	Outcome / Findings
Schilperoord, Rotmans and Bergman, 2008	Develop prototype of model	Explore model behaviour	MLP Haxeltine et al. (2008)	Regimes, empowered niches, niches Support canvas (consumers) Practice space	Complex aggregated agents for regimes and niches. SD-like structure for their internal dynamics. Simple Agents for consumers.	Replication of S-curves Exploratory example on transition to sustainable mobility
Bergman et al., 2008	Four historical examples (retrospective, taken from Geels and Schot 2007)	Replication of four transition pathways to test suitability of model	Schilperoord, Rotmans and Bergman, 2008 Narratives of the historical examples			Reproduction of qualitative dynamics of the four transition pathways as described in the historical examples
Köhler et al., 2009	Transition to sustainable mobility (prospective)	Assess pathways towards sustainable mobility	Schilperoord, Rotmans and Bergman, 2008 Data for UK (2000 to 2003) Personal communication with mobility experts Scenarios specifying future landscape developments			Assessment of likely transition pathways Policy implications
Timmermans, 2008	Connect societal transitions to punctuated equilibrium paradigm	Explore model behaviour	Linear System of Action (Coleman 1990)	Actors having interest in and control over issues	Extend Linear System of Action through variation and selection	Model self-organises into a critical state
Yücel and Chiong Meza 2008	Dutch waste management transition (retrospective)	Explore suitability of SD for modelling transitions	Aggregated data on implemented options Diverse concepts (e.g. multi-objective decision making)	Options (investments+stock) Actors (4 types) Environmental impacts	System Dynamics	Qualitative reproduction of waste management transition Identification of structural mechanisms behind transition (feedback loops)
Yücel and van Daalen, 2008	Transition from sailing ship to steam ship (retrospective)		Narrative on this transition (Geels 2002) and additional literature	Options Actors (2 types, 9 groups)		Replication of aggregated dynamics. Hypothetical scenarios to assess sensitivity

Authors	Topic	Purpose	Conceptual / empirical basis	Main model elements	Method	Outcome / Findings
Holtz, 2008	Transition from rainfed to irrigated agriculture in a Spanish case study (retrospective)	Identify relevant factors underlying transition	Case-specific literature Literature on (models of) agricultural systems and land-use change.	Farmers Options Rules	Agent-based	Confirms relevance of multiple levels and multiple factors for transition Questions relevance of niches, regimes
Chiong Meza and Chappin, 2008 **Chappin, Dijkema and De Vries, 2009**	Transition in power generation	Assess emission trading and carbon taxation as transition instruments	European emission trading scheme Dutch data on portfolio and markets Scenarios for electricity demand and fuel prices	Power producers Physical assets (power plants) Markets	Agent-based	The two policies both deliver but differ regarding the time when they unfold strongest effects
de Haan, 2008	Niche-regime interactions	Establish formalism for thought experiments	MLP Spatial approaches in political science Pattern-formation in physics, biology etc.	Regimes, niches Practice space	Partial differential equations	Provides precise mathematical description of transition theory concepts (e.g. regime)
Weisbuch, Buskens and Vuong, 2008	Product competition in a heterogeneous consumer population	Study dynamics of product competition	Increasing returns to scale	Three products Distribution of consumers' "willingness to pay"	Differential equations	Different dynamics dependent on parameters Multiple attractors may exist (Hysteresis possible)

Table 1: Overview of reviewed models.

purposefully reduce the dynamic flexibility of models striving for a complete understanding of the model's behaviour (de Haan, 2008; Holtz, 2008; Timmermans, 2008; Weisbuch, Buskens and Vuong, 2008; Chappin, Dijkema and De Vries, 2009). Others focus more on giving a complete and dynamic representation of the relevant domains and interactions (the MATISSE model; Yücel and Chiong Meza, 2008; Yücel and van Daalen, 2008). Weisbuch, Buskens and Vuong (2008) present the least extensive model focussing on the development of market shares of three products in a market of heterogeneous consumers with fixed preference distribution, while Yücel and Chiong Meza (2008) is the most encompassing work in terms of dynamic model parts included. It features dynamic attributes of options, a dynamic environment as well as a dynamic preference structure of four types of actors entailing context-sensitive decisions among options (those model parts are themselves composed of many dynamic sub-parts).

Different and partly contradictory conclusions are drawn in the various exercises. Increasing returns to scale turn out to be a central mechanism in some exercises (Weisbuch, Buskens and Vuong, 2008; Yücel and Chiong Meza, 2008), while others manage to generate "transitions" without explicitly considering this (Schilperoord, Rotmans and Bergman, 2008; Timmermans, 2008). Similarly, while the MATISSE model does not generate transitions without a landscape signal stimulating this (Schilperoord, Rotmans and Bergman, 2008), de Haan (2008) and Timmermans (2008) admit the absence of a landscape level in their models, but still generate dynamics they consider being transitions (or first phases of transitions, in case of de Haan).

This review of recent models has not lead to conclusions on what would be appropriate mechanisms to explain transitions. Speaking broadly, major differences relate to what is an appropriate level to define model parts: the entity-level of actors, technologies, institutions, market mechanisms etc. or the more aggregated level of niches and regimes? How broad should a model be in terms of levels and domains included? Further, are landscape signals necessary to induce transitions? All models present some evidence that lends them some plausibility. But obviously, given the diversity of model structures, one way or the other some convergence, combination and refinement is needed to reach common ground. The question to which degree and in which way an explanation of a transition can simplify the real process without neglecting key elements or processes could not be answered from this review.

3.3 Micro-macro interactions

The heterogeneity of model structures of the reviewed models reveals a limited shared understanding of what are essential elements and processes for understanding transitions. The following draws on transition literature to relate the niches/regime- and the entity-level in order to overcome the discrepancy in the structures of the reviewed models. The next sub-section relates the gained insights to the different approaches chosen in those models.

One pillar of understanding, which is common ground in transition research, is the importance of macro-level structures (i.e. regime, niches) influencing a micro-level of entities and channelling developments into specific directions. This view is reflected in the wide utilization of the MLP. Different types of higher-level dynamics structure the interactions of micro-level entities. The project SusTime (Nill, Haum and Hirschl, 2004) found confirmation that the techno-economic, the political and the socio-cultural domain each have internal dynamics which sometimes open “windows of opportunity” for change while at other times these sub-systems are more stable and resistant to change. The notion of a technological regime (Nelson and Winter, 1977; Dosi et al., 1988; Van de Poel, 1998) refers to such alignment of internal dynamics in the techno-economic domain and Kingdon (1995) discusses the internal dynamics in the political domain. It was further concluded in SusTime that not only the existence of such windows of opportunity in all domains but also their timing seems to be relevant for the success of transitions.

However, macro-patterns themselves do not produce dynamics, they do not act. As Geels states: *“Although processes at different levels can converge and create windows of opportunity for regime change, the actual linkages always need to be made by actors. Hence, the MLP needs to be filled in with more detailed actor-related patterns.*” (Geels, 2005b, p. 692). Hence, for a generative mechanism of a transition – which requires specification of acting entities – it is not sufficient to take macro structures like regimes and niches as given but the micro-level entities have to be considered in order to understand how structures decline and new structures emerge.

But how micro-level entities align and interact in creating macro structures is mostly unknown, although some first steps have been made. Geels (2004; 2005b) has made some attempts to structure the micro-level of transitions. The following discusses - following the structure in Geels (2004) - interactions of technologies, interactions of actors, different kinds of rules and finally interactions between actors, technologies and rules; complementing Geels where appropriate. Regarding the interdependencies of technologies, Geels (2005b) names complementarities between technologies, technical add-on and hybridization, sequential accumulation (one technology paves the way for others through opening up the dominant regime) and finally competing technologies which “borrow” technical elements from each other. Hillman (2008) similarly defines six modes of two-technology interactions based on species interactions defined in ecology (e.g. competition, symbiosis). Different kinds of technology interdependencies likely entail different modes of interaction of regimes/niches. Consider for example an increase in personal travel via public transport which reduces congestion problems, doing so actually increasing the utility of using private transport. In this example, a growing public transport niche may have ambiguous influence on a dominant private mobility regime whereas niches around electric cars and hydrogen driven cars can be assumed to compete for similar markets and resources (e.g. R&D effort).

The dynamics of destabilizing the old regime and building up a structurally different new one are driven by the actions of actors (like firms, consumers, associations, administration, politicians etc.). Geels (2005b) identifies eleven patterns of actor relationships (although this is only a first non-systematic collection), for example innovation races or a “cartel of fear” (all actors hesitate to make a first move due to many uncertainties and high risk involved). A coarse systematic distinction may be made between constellations of (few) corporate actors playing strategic games and collective behaviour - aggregated and self-organized behaviour of many myopic actors. For the latter several models exist, like diffusion of innovation models or the threshold models of Granovetter (1978) who has shown that change in the collective behaviour of a mass of actors is not a simple aggregation of individual behavioural changes. Instead it may be dependent on the specificities of actors' attributes and their interaction structure. Small differences may e.g. decide whether a bandwagon-effect is interrupted in an early stage. Those latter actor interactions feature first-order emergence (only), i.e. local interactions generate emergent macro-phenomena. In the former type of actor interactions, the strategic games, actors act (probably bounded-rationally) according to the overall macro-situation which is then influenced by their actions which in turn triggers adaptations of some actors' strategies. Hence, through reflexive actors' perception of the macro-situation, the macro-level has a direct feedback to the micro-level, so-called "second-order emergence" (Squazzoni, 2008b). Such macro-to-micro feedback is considered essential for understanding social systems and differentiates them from natural and biological complex systems (Mayntz, 2000). Few concepts and models exist. According to Mayntz (2004), the toolbox to analyse and systematize constellations of corporate actors and institutional settings is not very well filled. Both types of actor interactions play a role in transitions. Consumer behaviour and also competition of many small firms may be represented through collective behaviour. Other aspects, especially policy development, the work of associations and strategic behaviour of multi-national "big players" are likely more oriented towards the overall macro-situation. The importance of both types of actor interactions may vary depending on the field in which transitions are analyzed. Some sectors like water management feature mostly corporate actors while in others like mobility and agriculture the role of many, mostly unorganized actors like consumers and farmers becomes prominent.

Regarding rules, Geels (2004) differentiates formal /regulative from normative and cognitive rules (Scott 1995) in five different regimes[4] which results in fifteen kinds of rules. Examples for those kinds of rules are formal research programmes (a formal/regulative rule in the science regime), symbolic meaning of technologies (a cognitive rule in the socio-cultural regime) and companies own sense of itself (a normative rule in the technological/product regime). Those kinds of rules reflect issues considered relevant for different aspects of transitions and are more extensively elaborated in related strands of literature (e.g. sociology of technology and evolutionary economics). Geels (2004) further conceptualizes (bi-directional) interactions between actors, rules, and socio-technical systems in

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[4] In this article Geels uses terminology as follows: he distinguishes five different "regimes" being related in an overarching "socio-technical regime". Those regimes are: technological regime, user and market regime, socio-cultural regime, policy regime, science regime.

regimes and niches relating those to respective strands of literature (e.g. between actors and rules this resembles the sociological interplay of agency and structure).

It may briefly be noted that entities are not only forming regimes and niches but also constitute the links between regimes and niches and hence enable regime-niche interactions. Entities may interact across regime/niche boundaries e.g. in the following ways: through input-output relations, complementary technologies, actors involved in several configurations and regulations applying for several configurations (cf. e.g. Konrad, Truffer and Voß, 2008). If one elaborates entities' interactions with respect to the multitude of actors, technologies and rules mentioned above, it becomes apparent that the micro-cosmos of entities seemingly considered important in empirical and conceptual works is tremendously vast.

Although entities constitute and generate macro structures, it should be stressed (once more) that the structures involved in transitions (regimes/niches) are not only passive outcomes useful to describe transitions on a higher level of aggregation, but that they are actively involved in influencing developments through feedback to the micro-level of entities. The macro-level and its constituting micro-level are entwined.

3.4 Hitherto models do not provide explanations

The previous discussion shows that the *interaction* of regime/niche-level (macro) and the entity level (micro) is central to understanding transitions. Transitions are regime changes and this comprises disintegration of an old regime and creation of a new one – they are processes of decay and (re-)creation of structures. In these processes macro-level changes emerge from micro-level developments while macro-level developments influence developments on the micro level. This dynamic interaction between macro and micro-level is mostly neglected by the models reviewed in section 3.1.

The MATISSE model[5] - being based on regimes and niches interactions - circumvents the necessity to explicitly define acting micro-level entities through adding some internal dynamics to regimes and niches and embedding them into a “support canvas” representing consumers. But it uses many black-boxes which leave blind spots in the explanation of a transition provided by this model. The transformation from niche to empowered niche to regime (and reverse) and associated changes in behaviour, the internal metabolism of regimes/niches transferring “support” from the support canvas into institutional and physical capacity usable for regime/niche growth or for changing what a regime/niche does, as well as the behavioural models of regimes and niches are seemingly inspired by theory (e.g. Laver, 2005) and empirical work but are not explicitly validated against empirical evidence and the appropriateness of transferred theories is not discussed[6]. Some of the categories

[5] A similar line of argument as the following one can be developed for de Haan’s model.

[6] This may be due to reasons of limited space in publications.

introduced (e.g. institutional capacity) remain abstract and it would be difficult to relate them to observable units of empirical systems. The model further implements the artificial assumptions of ascribing actor-like coherence and the ability to act to regimes and niches. Haxeltine et al. (2008), describing the framework underlying the MATISSE model stress that the actions of niches and regimes reflect the emergent outcome of the activities and actions of many diverse actors within that subsystem. This is in line with proposing a coordinative function of regimes directing dynamics (e.g. technological development) into a specific direction; otherwise over time the regimes' and niches' practices would disperse all over the practice space. But when it comes to understanding transitions, a (or even *the*) crucial phase starts when the dominant regime begins to loosen and thus looses its coordinative function. Regime resources are redistributed partly depending on regime actors' activities, especially if the regime features important big players like the big companies of the energy and mobility regimes. Empirically it can be observed that actors may stick to the regime and try to defend their position e.g. through technological improvements (the sailing ship effect). But it can also be observed that actors diversify into various technologies; or that different actors follow different strategies (Geels, 2005b). The latter can be observed for the current land-based mobility system in search for alternatives to the gasoline driven car. While major automotive firms invest in ethanol vehicles, the natural gas and oil industries have lobbied the UK government to impose standards which constrain ethanol commercialisation (Whitmarsh and Nykvist 2008). Furthermore it can be observed that different car companies follow different strategies for developing low-emission vehicles (Pinske, Bohnsack and Kolk, 2009). This richness of possible reactions to declining regime power is ignored if macro-structures are the acting entities in a model.

The above discussed models focussing on the micro-level of entities neglect (mostly) the role of reflexive actors and strategic behaviour and remain close to an understanding of transitions as emergent outcome of unintended and unplanned actions of myopic actors. This may be appropriate for some transitions. The framework of Smith, Stirling and Berkhout (2005) distinguishes four "transition contexts" along two axes ("resource locus" and "steering of adaptive response"). The cases with "low coordination" on the "steering of adaptive response"-axis resemble unintended and unplanned transitions and may be modelled with little or no strategic behaviour of actors involved. But the higher the level of coordination among regime members, the less adequate such a simplification seems to be. Moreover, social scientists have highlighted that social macro phenomena are usually the outcome of an interaction of planned and unplanned actions, most often several actors act strategically in order to influence the macro situation in a specific direction (e.g. a new law is passed, a campaign is started), but the actual emergent outcome (further influenced probably through myopic actions of still other actors) is different from all intended outcomes (Mayntz, 2009). The micro-level models further do not incorporate an alignment of individual entities to macro-level structures and consequently do not consider a coordinative function of macro-structures – this stands in strong contrast to the focus on macro-structures in conceptual and empirical works on transitions.

To summarize, hitherto models focus either on regimes and niches or on the micro-level. What they do not address is how mutual adaptation of micro-level entities leads to integrated “configurations that work” (i.e. niches, regimes) which then eventually compete on a higher level and influence the micro-level in a way that sustains their existence. Therefore, the reviewed models fall short in capturing arguably essential micro-macro interactions. They further seem strongly simplified in light of the richness of entities and interaction patterns considered in conceptual and empirical works. Insisting on the sufficiency of one of the proposed model structures to capture the essentials of a transition would mean to question the relevance of most of the entities and interactions identified in conceptual and empirical works. If one acknowledges that there is a point in emphasizing the role of micro-macro interactions and in identifying such a diversity of micro-level interactions contributing to the formation of macro-structures, then it must be concluded that hitherto transition models do not constitute explanations for transitions as understood in this article. More likely they generate similar macro-dynamics as observed in transitions but the respective model structure does not resemble the underlying system structure[7]. The MATISSE model maybe deserves some special remark when making the claim that models are too simplified since it is rather a framework than a single model. The framework dissects a transition into a sequence of mechanisms which is a valuable step for dealing with complexity. It is further made explicit that the framework is open to extensions and that regimes and niches could be represented in greater detail using different sub-models than the ones used in the first implementations. The claim made is hence limited to the implemented models.

The degree of similarity between model structure and system structure required in a modelling exercise can in general not be defined without referring to the model purpose. Of course, models may well serve some purpose like testing of a method or exploring consequences of assumptions. A close resemblance of system structure and model structure is however required for an explanation of a phenomenon and is especially essential for model exercises venturing beyond the context used to specify the model (this is e.g. the case in prospective studies or if policy advice is given). Only if the model structure resembles the system's structure it can be expected that the model's response to some previously untested stimulus is (to a certain degree) in accordance with the real system's response.

4. Future routes in transition modelling

The previous sections have explicated that computer models are useful tools to enhance understanding of transitions and that a transition model provides an explanation of macro-changes by suggesting an underlying mechanism on the micro-level. A brief review of recent models did not lead to conclusions on what would be appropriate mechanisms to explain transitions and the subsequent discussion argued that those models are very simple compared to the richness of entities and processes considered in

[7] See section 4.1. below on the many-to-one relation of structure and emergent properties in complex-systems.

conceptual work and that they neglect essential micro-macro interactions. The obvious conclusion would be to extend models to incorporate the missing entities and interactions. Section 4.1 gives some arguments that building extended, broader models is not advisable given the limited knowledge on the micro-foundation of models and the limited means for validation. This leads to the conclusion that building a model that aims to provide a complete generative mechanism explaining a transition is over-ambitious. Therefore, it is recommended in sections 4.2 and 4.3 to abandon the goal to capture the overall dynamics of a transition process in a single model and alternative approaches for fruitful application of simulation models are suggested.

4.1 Complexity and uncertainty set limits to model extension

Transitions are processes in complex systems. A well-known problem for studying complex systems is a many-to-one relation between system structure and emergent behaviour, i.e. several structurally different systems might generate similar emergent behaviour and properties. This often leads to a coexistence of several reasonable explanations of the same empirical phenomenon because, as Sterman puts it, "*(t)he number of variables that might affect the system vastly overwhelms the data available to rule out alternative theories and competing interpretations*" (Sterman, 2000, p. 25). This equifinality (also called "under-determination problem" or "identification problem" (Windrum, Fagiolo and Moneta, 2007)) still pertains in modelling fields having a longer tradition than transition modelling, like modelling of environmental systems (Beven, 2002) and it can even be concluded from theoretical reasoning that the correctness of a model can never be finally proven (Oreskes, Shrader-Frechette and Belitz, 1994). Still, confidence in the explanatory power of models can be established; otherwise all modelling approaches would be futile. Although the details of a procedure best applied in a specific modelling exercise depends on the set-up of this exercise (e.g. the model purpose), broadly speaking, confidence can be built on the one hand through substantiating the appropriateness of a model's micro level foundation; and on the other hand through replication of emergent properties (e.g. Troitzsch, 2004; Yilmaz, 2006; Boero and Squazzoni, 2005). Although these issues related to the modelling of complex systems are not qualitatively different regarding transitions than regarding other types of processes, in the following it is argued that specification of the micro-foundation as well as macro-validation pose challenges which are especially pronounced regarding transition modelling and that thus the bandwidth of possible explanations is especially broad in this field (cf. Holtz et al., submitted for a more elaborate discussion).

The vast scope and inherent complexity of transitions is prominent as explicated in section 3.3. Which of the many entities involved are essential for a transition is however at best vaguely known and leaves much room for subjective assumptions. This is all the more the case since for many highly abstract key concepts - most notably "transition" itself as well as "regime" and "niche" - no shared definitions exist and (widely accepted) operationalizations are absent. Differences in the chosen specification of these concepts lead to model structures which are quite distinct, what raises the problem that conclusions derived from such distinct model structures are hardly comparable. Consider “transition”: sometimes a transition is defined as “regime change” (e.g. the MATISSE model) what shifts the problem to specify “regime change” (e.g. movement in the practice space) and to define which kind or amount of regime change is significantly strong enough to qualify as transition and not (only) as incremental change. In other cases single indicators, most often shares of technologies, are used to indicate a transition (e.g. Yücel and Chiong Meza, 2008). The freedom in defining a model’s micro foundation entailed by such conceptual vagueness is expressed in the multiplicity of model structures of the models reviewed above.

The amount of data or stylized facts to rule out competing explanations is limited. The defining characteristics agreed upon up to now by transition researchers (S-Form, multi-level and multi-domain interactions) are very general and therefore provide little guidance for the assessment of the explanatory power of different models. Anyway, regarding individual models, a validation using macro-properties must be discussed with regards to this model’s objectives. Some of the reviewed models are explicitly designed as “thinking tools” and do not address empirical cases (de Haan, 2008; Timmermans, 2008; Weisbuch, Buskens and Vuong, 2008). Those models are utilized to infer the dynamic implications of a certain set of assumptions and therefore, by design, need no explicit validation. Models that are reproducing specific cases (Bergman et al., 2008; Holtz, 2008; Yücel and Chiong Meza, 2008; Yücel and van Daalen, 2008) can be validated using empirical data which is more specific than general behavioural properties assigned to transitions. However, a problem arises from the limited amount of sources providing information on historical transitions. The same narratives are used to design a model and then to validate it (Bergman et al., 2008; Yücel and van Daalen, 2008). If not done carefully, this can turn out to produce tautologies. For example, a specific actor group is described to be the first to innovate. Then, while designing the model it is tempting to conclude that this group has a high preference for the innovation. Then, the simulation shows that this group is first to innovate, which is hardly surprising. This is not to say that the reviewed model exercises have acted in that manner but it can be observed that current modelling exercises are not very explicit regarding separation of empirical micro-foundation, model calibration and model validation. Further, due to the descriptive nature of narratives, those may be “dissected” using different analytical tools, leading to different conclusions on underlying mechanisms. For example, Bergman et al. (2008) as well as Yücel and van Daalen (2008) both report on modelling exercises replicating the transition from sailing ship to steam ship described by Geels (2002). But they utilise very different frameworks as base for their respective models and hence come up with very different model structures. Still, both studies conclude that the respectively used frameworks are helpful to structure the empirical knowledge and to inform model development. Since both exercises propose a somewhat plausible explanation for the overall transition it is again unclear how those may complement each other. In general, the vagueness of means for validation can be seen in the fact that, despite their obvious differences, all the reviewed models present some evidence that lends them some plausibility.

Models that would incorporate the missing micro-macro interactions sketched in the previous section 3 would be broader and more complex than the reviewed models. The discussion in this section shows that such an approach would rather increase than decrease the number of coexisting explanations. Considering more relevant entities, levels and domains would also mean to incorporate more degrees of freedom while the available information for substantiating the micro-foundation of models as well as for validation using macro-properties is limited and often requires further specification before it is usable for informing model development. The huge gap between the overall defining properties of transitions (S-form development, multi-level, multi-domain) and the multitude of micro-mechanisms that are able to match and/or generate those properties is a major drawback for the assessment of generative mechanisms for transitions. Therefore, building broader models seems not to be a reasonable way ahead. The question remaining for transition modellers is thus how model building can advance our understanding in the current situation.

4.2 Building blocks of explanation

It should first be acknowledged that essential entities and processes may well vary across cases and that there is no general transition model which is both capturing essentials of transitions in (almost) all cases and providing a complete explanation based on entities interactions. The discussion in section 3.3 has mentioned the role of corporate actors as being somewhat different regarding water management compared to mobility. Other differences between cases may arise from the existence and “reusability” of large-scale infrastructure and from other specific characteristics of transitions in specific fields. Still some patterns may remain similar, e.g. niche-regime interactions and a positive feedback between price/performance ratio of technologies and their spread. It is beyond the scope of this text to elaborate further on similarities and differences between cases. The point here simply is that on the one hand different societal sub-systems involve different types of entities and hence require consideration of these differences in respective explanations but that on the other hand similarities exist which can be generalised across (some) cases.

Hence, using building blocks of explanation may be a suitable strategy to cope with the contingent and idiosyncratic nature of social processes in general and of transitions in particular while not “reinventing the wheel” for each further case-study. Building blocks render classes and characteristics of transition (sub-) processes. They constitute a middle ground between the micro-level and overall transition dynamics and can help to connect those other levels. They specify classes of similar micro-level constellations and provide a scheme to study those. For example, when studying interactions between regimes and niches, the conceptual distinction between structural coupling (via actors involved, elements shared) and functional coupling (e.g. via competition for resources and markets) might guide the analysis. In turn, studies of the micro-level likely will enhance understanding of building blocks (e.g. identify other types of couplings). Building blocks then also potentially allow for (careful) abstraction of constituting micro-processes when analysing overall dynamics; e.g. structural coupling and functional coupling might be abstracted from the specific underlying entities and processes when modelling how niches may pressure a regime.

Conceptual, empirical and theoretical work in transition research has identified a bunch of building blocks for understanding transitions which can partly also be found back in the reviewed transition models. On a high level of abstraction those are for example the relevance of the kind and timing of multi-level (Geels and Schot, 2007) and multi-domain interactions (Nill, Haum and Hirschl, 2004; Kingdon, 1995; Konrad, Truffer and Voß, 2008), the role of visions and expectations (Berkhout, 2006; Truffer, Voß and Konrad, 2008), the role of transition contexts (Smith, Stirling and Berkhout, 2005) and potentially still others. On lower abstraction levels one finds recurrent patterns as e.g. self-reinforcement of option prevalence through heterogeneous actors and increasing returns to scale, the patterns of interactions of technologies and actors identified in Geels (2005b) and by Hillman (2008) and also many insights from disciplines integrated in transition research (see e.g. Geels (2004) for relations between actors, rules and technologies and respective references to strands of literature dealing with those relations).

All of those building blocks have credibility and the question surely is not whether one *or* the other is explaining transitions best. Instead, building blocks may eventually be combined to explain system innovation cases based on the specificities of that case entailing a particular form and relevance of the (interaction) of involved building blocks; while explanations of the processes underlying each building block are available if a regression to lower levels of abstraction is required. Through partitioning of an overall complete explanation, building blocks facilitate deriving a complete explanation without entering the realm of excessive complexity. Such experiences have been made in other strands of the social sciences which aim to explain large-scale social phenomena through "dissecting" them into mechanisms (Hedström, 2008). The most promising way ahead is to develop a set of generalized mechanisms which can be used as "tool-box" to explain specific instances of those social phenomena (Hedström, 2008; Scharpf, 2002).

Therefore, the challenge is to enhance our understanding of building blocks of explanation, to relate them, to identify the contexts and situations in which each of them becomes relevant and to explicate their role in the overall process. Then, individual cases may be explained based on the specificities of that case entailing a particular form and relevance of the (interaction) of building blocks.

Building blocks of an intermediate level of complexity are promising to bridge the gap between the overall properties of transitions and the multitude of entities and processes on the micro-level (cf. also Haxeltine et al. (2008) for a similar line of argument). But currently the knowledge on the relation between building blocks and overall properties, between building blocks and the micro-level and on the relation between various building blocks of explanation is sketchy, at best. It is beyond the scope of this article to give an exhaustive overview of current conceptual developments. The point to be made here is that there is an open wide field of potential modelling applications involving building blocks.

First, models can help to structure the ontology of transitions, i.e. to identify the essential elements and processes underlying transitions. It has been discussed in section 3.3 that the cosmos of micro-level entities potentially relevant for transitions is tremendously vast. A shared knowledge base of essential elements and processes is currently mostly absent in transition research. Building blocks of explanation can serve as focus to identify micro-level entities required to understand the characteristics described by this building block. For example the transition contexts distinguished by Smith, Stirling and Berkhout (2005) make a distinction between cases along the axis of “high” or “low coordination” of regime actors. This identified relevance of coordination among regime actors provides a focal point to study which entities and processes are involved in generating such coordination. Simulation models can help to connect the level of entities and that of emergent properties such as coordination. Using simulation models might hence help to structure the ontology of transitions and to distinguish essential entities and processes from negligible ones.

Second, models might be used to study the relation between building blocks, for example how the conceptual distinction between structural coupling and functional coupling of niches and regimes (see above) enriches the picture of kind and timing of multi-level interactions according to Geels and Schot (2007). This idea to study the relation between building blocks without causal regression to the level of entities rests however upon the assumption that building blocks can be represented and related on a higher level of aggregation without neglecting essential interactions. Hence, analysing the combination of building blocks requires first of all a sound understanding of each building block involved. This understanding may serve to define appropriate abstractions which adequately capture the respective role of a building block in various contexts.

Summarizing, the suggestion for the application of models is to design model exercises whose objectives are not to provide a complete generative mechanism of a transition directly but which instead would aim at advancing our understanding of (relations between) building blocks of explanations.

4.3 Suggestions for modelling exercises

The remainder of this section becomes more specific regarding how such modelling exercises can be designed. It explores two kinds of modelling exercises which are considered feasible and fruitful given the current state of knowledge of transition research. A discussion on how they (would) meet the challenge of complexity reduction while at the same time enhancing our understanding is included.

Simulating historical cases

As mentioned before, historical transitions have usually been “explained” through some form of narratives. However, transitions are processes in complex systems. Overall change emerges from interactions of multiple processes across various scales and domains. Non-linearities and emergent properties easily overrun the capability of the human mind to fully grasp such complex dynamics.

Hence, narratives might sound plausible but it is difficult to assess whether indeed the dynamics described are generated by the entities and processes argued to generate them.

Narratives are usually developed using frameworks (multi-level, multi-phase (e.g. Rotmans et al., 2001; Van der Brugge, Rotmans and Loorbach, 2005)) to structure the empirical case. By re-checking completeness and possible contradictions in the “explanation” of (parts of) a historical case in a modelling exercise, aspects of a mechanism that play a role in the historical process but which are neglected by a specific framework may be identified. Following that line, models can help to sort out “wrong” or incomplete explanations of historical transitions and help to identify missing parts and interdependencies. This can hint to gaps in the frameworks used to structure empirical research. Models of historical cases can ultimately help to improve frameworks and can hence enhance the conceptual base of transition research. For example, the MATISSE models implement the multi-level structure and basic theorizing on interactions of these levels. However, in the course of the modelling exercise, they added the level of “empowered niche” which is not present in the original framework. If it could be substantiated that in order to generate transition dynamics empowered niches need to be introduced as level which is qualitatively different from niches and regimes, then this would suggest reconsidering the most-widely used framework in transition research. The MATISSE model exercises differ however in their objectives from the ones proposed here in that the objective suggested here is to deliberately put a framework like the multi-level framework to a test which was used to structure the narrative; instead of using a framework somewhat unquestioned for prospective studies (Köhler et al., 2009) or for experiments and potentially stakeholder interactions (Bergman et al., 2008). Actually, the definition of “empowered niches” described above was merely a by-product of model-development and to the author’s knowledge did not stimulate a debate on the structure of the multi-level framework.

Regarding reduction of complexity and regarding validation, such an exercise as proposed here benefits from a close backing through an empirical case. An empirical case that is already described from a transition perspective gives good indications of relevant elements and mechanisms on the micro-level and will report on case-specific emergent properties of the process which can be used for validation. Further, generation of innovations does not need to be modelled endogenously since the innovations that appear during the transition are known from hindsight knowledge. The same holds for strategic behaviour of main actors and landscape developments. This provides possibilities for reduction of model complexity by specifying certain developments and events in scenarios, externalizing them from the model.

Scrutinizing general (partial) mechanisms

A second approach is using models to test and improve proposed general mechanisms explaining some emergent macro behaviour through specific circumstances. Weisbuch, Buskens and Vuong (2008) is an example of such a modelling exercise. It advances our understanding of the interplay of heterogeneity of actors, increasing returns and the occurrence of multiple attractors in technological substitution. Models can be used to test whether and if so under which conditions emergent properties and dynamics can be observed. The base of original transition research concepts usable for such modelling exercises is still limited but rapidly growing. Current well-known frameworks like the multi-level and the multi-phase framework operate on a very high level of abstraction and claim to be relevant for all transitions. But they do not provide sufficiently detailed information to build models based (only) on information provided by such a framework. Refinements of these concepts and alternatives that have been proposed (e.g. Smith, Stirling and Berkhout, 2005; Geels and Schot, 2007) go one step further, specifying different circumstances that lead to different transition paths. These concepts still operate on a very general and qualitative level. However, stylized models could be built to reproduce and compare proposed relationships between circumstances and resulting transition dynamics. Furthermore, the diversity of interactions between actors, between technologies and between actors, technologies and rules sketched in section 3.3 provides plenty of possibilities to define modelling exercises which limit themselves to some sub-field of transitions.

Such models are thinking tools to explore the dynamic consequences of specific assumptions. Validation using empirical data is not an issue since such models would not claim that their structure resembles reality but only that it is a formalization of a certain hypothesis. Still, a major challenge resides in the vagueness of underlying concepts. This vagueness of concepts allows multiple representations in a computer model. There is a gap between the level on which frameworks operate and the level on which computer models have to be specified which has to be creatively “filled” by the modeller, including subjective decisions and assumptions. A computer simulation model is a model of the underlying concept (Küppers and Lenhard, 2005). Computer simulation models can not logically prove or disprove the validity of their underlying conceptual base. However, ambiguity in translation of concepts into computer models can be diminished through identification of sensitive assumptions and variation thereof. This would imply classical sensitivity analyses dealing with parameter values; but should be complemented by exercises varying the more fundamental assumptions manifested in a model’s structure. The explanatory power of single models might be limited, due to the above mentioned reasons; but a multitude of models and model variations may confirm and/or refine the current conceptual base significantly.

5. Conclusions

Computer models provide an approach that can help to address certain short-comings of qualitative approaches utilizing frameworks and narratives. They require an analytical view on the system and the stringency involved in defining a model leads to precise formulations which are testable and allow for generalizations. Computer models further allow to actually *explain* emergent transition dynamics by proposing generative mechanisms on the micro-level. However, recent modelling exercises do not agree on what would be constituents of such mechanisms. Broadly speaking they differ regarding the level adopted (actors, technologies etc. or niches and regimes) and regarding the broadness in terms of diversity of processes and domains involved. This article has argued that the interaction of regime/niche-level (macro) and the entity level (micro) is central to understanding transitions and that this aspect is mostly neglected by the reviewed models. What those models do not address is how mutual adaptation of entities of different domains leads to the formation of niches and regimes which then eventually compete on a higher level and influence the micro-level in a way that sustains their existence. Therefore, they fall short in capturing an arguably essential characteristic of transitions. Moreover, the models seem strongly simplified in light of the richness of entities and interaction patterns considered in conceptual and empirical works.

Building extended, broader models is however not advisable given the limited knowledge on the micro-foundation of models and the limited means for validation. This has led to the conclusion that building a transitions model that aims to provide a complete generative mechanism explaining this transition is over-ambitious. The gap between the micro-level and overall transition dynamics seems to be too big to be captured by one big “jump” (i.e. one model aiming to explain transitions in their totality). Instead, it is recommended to abandon the goal to capture the overall dynamics of a transition process in a single model.

This article then has suggested to more deliberately making use of building blocks of an intermediate level of complexity – e.g. timing and kind of multi-level interactions – to advance our understanding of transitions. Transition modelling can contribute to the necessary conceptual clarification of identifying, understanding and relating those building blocks and it is suggested to design model exercises which enhance our understanding of specific building blocks or of the relations between building blocks. Two specific suggestions are made: 1) Replicating empirically analysed historical transitions. This can ultimately lead to improvement of frameworks used for the empirical work. 2) Modelling of general (partial) mechanisms for testing and refining links between some constellations and emergent macro-level phenomena. This can help to assess suitability of proposed mechanisms as (partial) explanations of transition dynamics.

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Paper 3: Specifying Regime

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Paper 4: Guadiana Model

Holtz, Georg and Claudia Pahl-Wostl, "Using an agent-based model to analyse the role of farmers' characteristics for land-use change in an agricultural system and for related groundwater over-exploitation", resubmitted to *Environmental Modelling and Software* (date of resubmission of revised version: October 19th, 2009)

Using an agent-based model to analyse the role of farmers' characteristics for land-use change in an agricultural system and for related groundwater over-exploitation

Georg Holtz[1] & Claudia Pahl-Wostl
Institute of Environmental Systems Research, Barbarastrasse 12, 49076 Osnabrueck, Germany

Abstract

Irrigated agriculture is a main user of groundwater. Achieving a sustainable use of groundwater will often require agricultural land-use changes such as shifting to entirely different kinds of crops and/or technologies. Enhanced understanding of land-use change is hence required for developing policies for a sustainable water future.

In the study presented we use an agent-based model to investigate the history of irrigated agriculture in the Upper Guadiana Basin, Spain, in order to learn about the influence of farmers' characteristics (inter alia profit orientation, risk aversion, skills, available labour force and farm size) on land-use change and associated groundwater over-use in this region. The main findings are that no single factor is sufficient to explain the empirically observed land-use changes but that interactions of factors have to be considered. It is further shown that different types of farms existing in the UGB can be expected to exhibit distinct responses to drivers of land-use change and that it is therefore important to acknowledge heterogeneity of farm types when aiming at influencing land-use changes. Although the more specific findings are open to debate due to methodological reasons, it can be concluded that a sound understanding of the social system making use of a resource is required to solve problems of resource over-use. This article demonstrates that agent-based models can be utilised as thinking tools even in situations of scarce and uncertain data that are often encountered when dealing with resource use problems.

Keywords: Agent-based model; Land-use change; Agriculture; Groundwater; Upper Guadiana; Mancha Occidental Aquifer

[1] *Corresponding author.*
E-mail: Georg.Holtz@usf.uos.de. Phone: +49 (0)541 969 3413. Fax: +49 (0)541 969 2368.

1 Introduction

Irrigated agriculture is the main user of groundwater in many parts of the world (World Water Assessment Programme 2009) and in some cases accounts for up to more than 80% of groundwater use (Llamas and Martínez-Santos 2005). In arid and semi-arid regions this can lead to aquifer over-exploitation. Then, reduction of groundwater use is essential for mitigating water quantity and -quality related problems and for achieving sustainability. Much of the required reduction in groundwater withdrawals has to be achieved in the agricultural sector. The amount of water needed for irrigated agriculture is strongly related to the irrigated area, to the water needs of crops planted and to the irrigation technologies used. Achieving a sustainable use of groundwater will often require changes that go beyond improving efficiency of water use but imply land-use change such as shifting to entirely different kinds of crops and/or technologies with different practices, organization of labour and distribution channels. Hence an enhanced understanding of land-use change is required in order to develop policies for a sustainable water future.

The Mancha Occidental aquifer (MOA) in the Upper Guadiana Basin (UGB), Spain, is such a case of groundwater overexploitation. There, since the 1970s, the irrigated surface has increased and farming practices have changed towards water-intensive crops. This development has lead to an over-exploitation of groundwater resources. In order to improve the situation, a change in land-uses reducing groundwater extractions is aspired in a recently approved "Special Plan for the Upper Guadiana" (Confederación Hidrográfica del Guadiana 2008) whose elaboration was included in the National Hydrologic Plan of 2001. Aldaya and Llamas (2008) have argued similarly that a paradigm shift towards "more cash and nature per drop" is needed and that an increase of the planting of high-value horticultural crops would provide a means to that end since they could provide more income on a smaller irrigated area while using less water.

Changes in agricultural land-use as those aspired for the UGB arise from a complex mix of influential factors from the economic, institutional (formal and informal rules), the technological and socio-cultural domain (e.g. Edwards-Jones 2006; Rogers 1995; Garforth and Rehman 2005; see section 4). However, there is no (sophisticated) generalized model that would allow explaining such changes. In order to enhance understanding on prospective land-use changes in a specific case, one strategy is to learn from the history of this farming region. For example, in the MOA, the predominant crops have been cereals (mostly winter cereals) and vineyards, although these crops have been less profitable than horticultural crops. Identifying reasons that have prevented a shift to more profitable crops in the past is highly relevant in the context of future land-use change scenarios.

In the study presented in this article we investigate the history of irrigated agriculture in the MOA in order to learn about factors influencing land-use change and associated groundwater use in this region. Our point of departure is that farmers play a central role as they are taking irrigation decisions. They are influenced by high-level developments, especially (changing) policies and they are exposed to upcoming innovations which they might adopt to improve their business. But ultimately decisions on crops planted and technologies used are made at the farm level and thus farmers are key actors bringing about land-use change and associated changes in groundwater extractions. Understanding developments and decisions at the farm level is vital for taking influence on groundwater extractions.

This study develops an agent-based model to study the respective roles and interactions of factors identified as potentially relevant for agricultural land-use changes in the MOA. Following the above reasoning, its main focus resides at the farm level. The study presented more specifically explores the influences of farmers' characteristics on the dynamics of land-use change. Those characteristics are identified and discussed below (see section 4) and comprise inter alia profit orientation, risk aversion, skills, available labour force and farm size. A model facilitates the exploration of the effects of considered factors while accounting for potential interactions among them, what can not easily be achieved with less formal methods due to the inherent complexity. How models can be applied - e.g. for prediction or exploration- depends on the available theoretical and empirical knowledge and data. The case of the MOA analysed in this paper is quite representative regarding the data situation in many cases of resource use dynamics. Data is scarce and uncertain (see section 3.2). Furthermore, it is also representative regarding the important role of human behaviour and the existence of multiple approaches for its representation. The literature contains a wide range of alternative models of farmer decision making ranging from mathematical programming (e.g. Balmann 1997; Berger 2001; Berger, Birner et al. 2007; Happe, Kellermann et al. 2006), genetic programming (Manson 2005), multi-criteria analysis (Rehman and Romero 1993) over different kinds of heuristic approaches like satifycing (Gotts, Polhill et al. 2003) and imitative behaviour (Gotts and Polhill 2009), implementations of socio-psychological theories like the theory of reasoned action and the theory of planned behaviour (Jackson, Quadus et al. 2006; Fielding, Terry et al. 2005) to semi-qualitative approaches (Elbers and Ernst 2008). Such a situation implies that the analyst is faced with a wide range of degrees of freedom what to include in or exclude from the analysis and a simulation model. This article shows how agent-based models can be utilised as thinking tools even in situations of scarce and uncertain data and given a variety of theoretical approaches. We develop a modular approach that allows studying influences of various factors to be analysed but also of impacts of variation of the implementation. This article presents the overall model structure, the modular decision-making algorithm and some simulation results obtained from the first realised model implementation.

This article in the following first outlines the case of the Upper Guadiana Basin (section 2). It then turns to describing and motivating the chosen methodological approach (section 3) and the conceptual building blocks underlying the model (section 4). The model implementation is explicated in section 5. Section 6 reports on simulation results and section 7 discusses the methodological approach and interprets simulation results. Section 8 summarizes the main findings.

2 The Upper Guadiana Basin

The Upper Guadiana Basin (UGB) is a rural area located in the Autonomous Region Castilla La Mancha in central Spain. Irrigation of farm land accounts for approximately 90% of total groundwater use while irrigation using surface is hardly significant (Llamas and Martínez-Santos 2005). During the last decades, the amount of irrigated farming has increased and farming practices have changed towards water-intensive crops, especially in the Mancha Occidental aquifer (MOA), the area's main aquifer which accounts for 90% of the UGB's groundwater extractions (Acreman 2000). This development has lead to an over-exploitation of groundwater resources in the MOA and has endangered wetlands of high ecological value (Llamas and Martínez-Santos 2005; Martínez-Santos, de Stefano et al. 2008). Although hydrological and climatic factors (e.g. droughts) are important to understand particular aspects of the problem, the decrease in groundwater level is strongly related to changes in farming land-use patterns; that is, changes in crops planted and in irrigation technology used determine the amount of water that is pumped from the aquifer and "lost" due to evapotranspiration. A sustainable situation can not be reached without significant changes in agricultural water use for irrigation (Bromley, Cruces et al. 2001; Lopez Sanz 1999).

The development can be ascribed to a combination of factors. Irrigation and pumping technology became widespread since the 1970s. Irrigated agriculture encompassed the possibility to plant water-intensive crops like maize, alfalfa and melons which did not grow in the region before that time. It further provided the possibility to achieve higher yields of traditional crops like winter wheat and barley as well as of vineyards and olives. Formal rules have also been changing; most notably the EU Common Agricultural Policy (CAP) had considerable influence on the profitability of various kinds of crops, during some periods favouring water-intensive crops, especially maize (Varela-Ortega 2007). To counteract, legal regulations and subsidy schemes were introduced to reduce the amount of water used by farmers. In particular in 1985 a new law was introduced and water passed from being a private good to be a public one, including the authorization of river basin authorities to limit allowed groundwater withdrawals. However, many farmers did not and still do not accept this law. They disagree with the obligatory pumping restrictions introduced in the MOA and take more water than granted (Llamas and Martínez-Santos 2005; WWF 2006). An agro-environmental programme (AEP) that compensated farmers for voluntarily reducing groundwater extractions was more successful in temporarily reducing the irrigated area and groundwater extractions. The overall developments have lead to a non-sustainable situation. Clearly, there is a tension between (short-term) socio-economic benefits from irrigation and avoiding potentially irreversible environmental damages. Current endeavours in the region aim at strategies reducing the environmental burden without constraining socio-economic prosperity too much (Confederación Hidrográfica del Guadiana 2008; Martínez-Santos, Llamas et al. 2008).

Figure 1 shows the development of irrigated area and the amount of groundwater extracted from the MOA from 1978 to 2005 and relates it to an estimate of a sustainable groundwater extraction level. If the current level of extractions is maintained, wetlands can not be recovered and ultimately also water resources will become insufficient for farming purposes. Table 1 relates changes in irrigated agriculture to policy changes. It is noteworthy that cereals dominate despite their comparatively low profitability (see figure 2 in section 6).

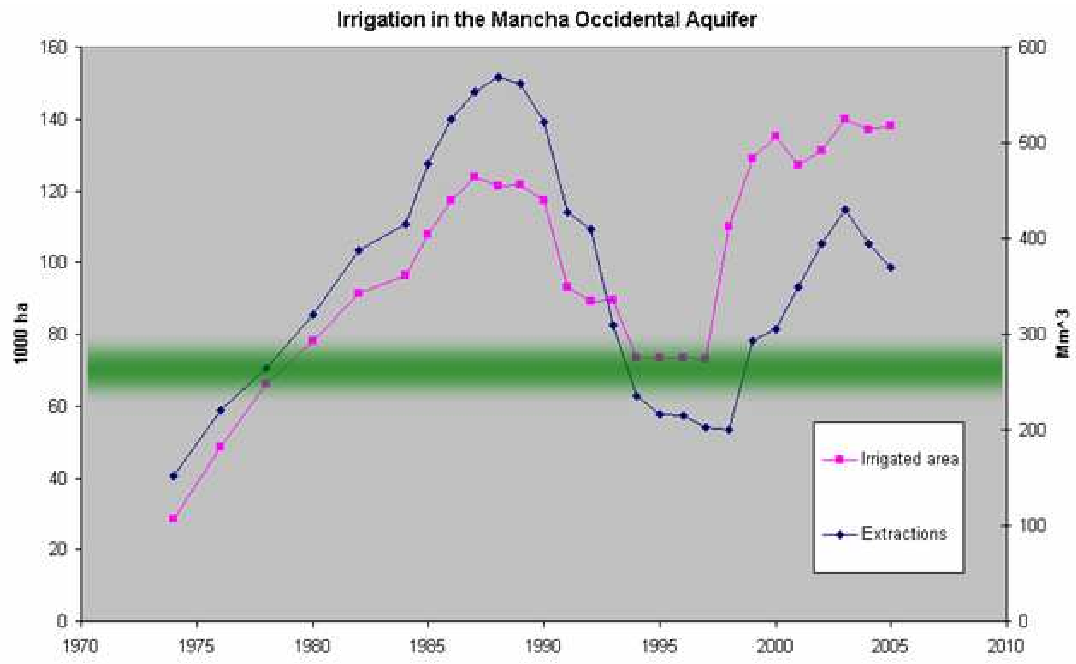

Figure 1: Irrigated area and water extractions in the UGB's main aquifer. The shaded area represents estimated renewable water resources (sources: Llamas and Martínez-Santos 2005; Varela-Ortega 2007; Baldock, Caraveli et al. 2000).

Time period	Main policy changes	Total irrigated area (cf. fig.1)	Irrigated crops (source: Llamas and Martínez-Santos 2005)
up to 1990	Groundwater becomes publicly owned in 1985 Spain enters EU CAP in 1985	Increase from ca. 30.000 ha (1974) to 125.000 ha (1990)	Traditional cereals (max ~35.000ha), high-yield cereals (max ~30.000ha), vineyards (max ~25.000 ha), sugarbeet (max ~17.000ha), melons (max ~18.000ha) Water intensive crops (high-yield cereals, sugarbeet, melons) appear as innovation in the area
1991- 1994	Pumping quotas (since 1991) CAP: COP intervention prices reduced, set-aside obligation, compensatory payments (1993- 1995) AEP1 (since 1993)	Drops to ca. 65.000 ha	High-yield cereals, sugarbeet disappear mostly Melons drop to approx. 1/2 of previous area Traditional cerals, vineyards drop to approx. 2/3 of previous area
1995-2001	Law banning irrigation of vineyards abandoned (1997) AEP1 payments increased (1997) CAP: COP intervention price further reduced, compensatory payments increased (2000-2002)	Increase to ca. 130.000 ha	Traditional cereals and vineyards increase to approx. twice their previous area
2001 onwards	AEP1 payments increased (2001) AEP2 (since 2003)	Remains approx. stable	Remains approx. stable (data up to 2003 only).

Table 1: Policy changes and associated changes in irrigated agriculture. See appendix for details of policies.

3 Methodological approach

3.1 Data availability

The UGB case is marked through scarce and uncertain historical data on land-uses and water usage. A reason for this is that implementation of groundwater based irrigation has been a "silent revolution" (Llamas and Garrido 2007) driven by private initiative of farmers without much intervention, control or monitoring through the government until the mid 1980s. With the 1985 Water Act Spain started to register water uses but more than 20 years later the registries are still incomplete (Hernández-Mora, Martinez-Cortina et al. 2007). According to Hernandez-Mora et al. the White Book on Water in Spain (MMA 2000) estimates that of the 500.000 operational wells existing in Spain only 50% had been declared and less than 25% had been registered and the situation is still not resolved today. Regarding the MOA, nearly 40.000 wells exist out of which only 17.000 are legally registered and also legal ones often do not have metering devices (Martínez-Santos, de Stefano et al. 2008). Also the extent of the irrigated area is prone to uncertainties due to the existence of illegally irrigated areas. In an attempt to assess the total irrigated area in the UGB the "Special Plan for the Upper Guadiana" (Confederación Hidrográfica del Guadiana 2008) reports on numbers[2] varying between 189.450 ha and 262.868 ha. This leads to high uncertainties regarding actual groundwater extractions. For example, according to Llamas and Martínez-Santos (2005) it is generally recognized that the all-time pumping maximum took place around 1988 but the estimations of this maximum vary between 570Mm^3 and 650Mm^3.

Historical data on land uses are scarce, too. According to the authors' knowledge time-series on crop distribution are available only from 1990 onwards and only for the (much bigger) area of Castilla La Mancha. The cropping pattern in the MOA is expected to differ from these figures due to the especially good accessibility of groundwater and the associated intensity of irrigated agriculture as well as due to the prominent role of vineyards. Data on irrigated crops in the MOA is available (see figure 3 in section 6), but given the uncertainty regarding illegal irrigation its exactness is doubtful. In sum, data is scarce and afflicted with uncertainties regarding water extractions, irrigated area and cropping patterns.

3.2 A flexible, transparent model

Computer models provide the possibility to run simulations which produce dynamic patterns and time-series. As such they enable the study of linkages between a set of assumptions (e.g. on farmer's objectives) and emergent properties of a system's dynamics like land-use change. Limited data

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[2] Note that both numbers are considerably higher than the ones presented in figure 1 since that figure covers the MOA only and is based on official data likely underestimating the actual magnitude of pumping.

availability however poses challenges for model specification and validation and must be considered in the modelling approach chosen. We follow the strategy to develop a flexible and transparent model. Transparency refers to the possibility to relate simulation results to model assumptions and parameter values. Through this, insights do not rest upon an uncertainly-laden "black box" model used to generate them. To achieve transparency, model complexity should remain modest. The modelling approach should further be flexible in order to incorporate all available information from various sources, "hard" data as well as qualitative information, general insights from the literature as well as case-specific information. It should further be flexible in the sense of providing the possibility of incorporating alternative assumptions, e.g. on actor rationality, in order to assess impacts of such assumptions.

Another issue to be considered is validation. We do not aim at exact reproduction of empirical data sets (e.g. on groundwater extractions). Given the fact that data is afflicted with uncertainty in the magnitude as described above, the goodness of a fit with empirical data is not necessarily meaningful anyway. Instead we aim at qualitatively reproducing patterns and trends in the empirical data what allows assessing in an explorative approach the influence of different factors on system dynamics.

3.3 Agent-based modelling

Agent-based modelling (ABM) is a suitable approach to incorporate various sources of information (Berger 2001) and offers s a versatile approach to represent the richness of human behaviour and the interactions of human behaviour and environment. ABM is a very flexible methodology utilized in modelling exercises showing a remarkable bandwidth regarding scales (number of actors represented, spatial, temporal), levels of abstraction chosen, field of application, complexity of representation etc. (e.g. Epstein and Axtell 1996; Holland 1996; Gilbert and Troitzsch 1999; Janssen and Ostrom 2006; Gurung, Bousquet et al. 2006; Feuillette, Bousquet et al. 2003; Happe, Kellermann et al. 2006; Bithell and Brasington 2009). ABM of land-use change is a comparably young approach (cf. Parker, Manson et al. 2003; Matthews, Gilbert et al. 2007). Nevertheless there has already been a progression from relatively abstract representations to applications to specific cases drawing on empirical data (Matthews, Gilbert et al. 2007). Agent-based models of land-use change usually feature on the one hand agents representing the decision making units (usually households) and on the other hand a spatial representation of the study area as well as inter-agent processes (e.g. land-markets, behaviour imitation) and interactions of agents and environment. They can be highly complex, mirroring the complexity of factors involved in real processes. The more aspects are considered, the higher the burden to specify parameters using empirical data and the bigger the challenge for model verification and validation.

In order to limit complexity and to account for limited data availability the model presented here does not explicitly represent space. An explicit spatial representation would primarily be relevant if spatial patterns in the process outcome were of interest. Regarding groundwater extractions this is not the case. It would further be useful to analyse structural change in the agricultural sector including increasing farm sizes through land redistribution as done e.g. by Happe, Kellermann et al. (2006). Indeed farm sizes in Spain are changing in the considered time frame; however, the process is rather linear and clear in its trend towards less small and more big farms (Eurostat). In contrast to that, the dynamics of groundwater extractions in the MOA are non-linear with ups and downs (cf. figure 1). Together with the non-appearance of structural change as driver for land-use changes in the case-specific literature, we conclude that for the problem analysed here change in farm sizes may be disregarded. Also other reasons, like upstream-downstream relations of water users, do not apply as reasons for a spatial representation.

Comparison of our model to existent models (most of which are spatially explicit) is hence difficult. Our model is used as a thinking tool. We explore relations between (assumed) farmers' characteristics and overall model dynamics. Comparing model dynamics with patterns in empirical data we draw conclusions on potential explanations for the empirically observed patterns. Our model is related to agent-based models of agricultural economists in studying agricultural land-use change in a specific region using empirical data (Balmann 1997; Berger 2001; Berger, Birner et al. 2007; Happe, Kellermann et al. 2006). In an initial study Balman (1997) presented a model used for theoretical analysis of agricultural structural change. Applications of extended versions of this model to empirical cases use the assumed appropriateness of the model structure implemented in this model and the robustness of the model against parameter variations to investigate policy scenarios starting from an empirically calibrated base year. However, those works are prospective whereas we aim at learning about the case-study region through a retrospective study. We study effects of varying model structure and parameters, comparing dynamics with longitudinal empirical data. This is more in line with some agent-based models designed to study historical settlement pattern (Diamond 2002; Dean, Gumerman et al. 2000) or the model on deforestation and afforestation of Hoffmann, Kelley et al. (2002).

4 Conceptual building blocks

The case-related literature unisono mentions availability of pumping and irrigation technologies and policies (Water act, CAP, AEP) as major drivers of land-use change (e.g. Llamas and Martínez-Santos 2005; Varela-Ortega 2007). We use these insights as starting point and aim at enriching the picture through a representation of farm related factors and processes.

4.1 Farmers' adoption of policies and innovations

Research on farmers' decision making and their adoption of policies and innovations forms a strand of literature in which economic approaches assuming the profit-maximizing farmer for long have played an important role (Edwards-Jones 2006; Janssen and van Ittersum 2007). Since the 1990s, a considerable range of complementary factors has been identified empirically, ranging from socio-demographics and the psychological make-up of the farmer, over characteristics of the farm household and the structure of the farm business to the wider social milieu (Edwards-Jones 2006). However, little is known about the relative contributions of these various factors in varying contexts. As Janssen and van Ittersum (2007, p.629) state: *"Our understanding of farm decision making is still limited…"*.

Nevertheless, what can be concluded from this strand of literature is that in western developed countries profit is indeed of major relevance for farmers' decision making. But it can also be concluded that a model on land-use change should incorporate other behavioural objectives as well. In this section we use available information on the UGB case to select some of the many potentially influential factors. The impacts of the selected factors are then further investigated using the model as described in the following sections.

García-Vila, Lorite et al. (2008) provide results of recent semi-structured interviews of (southern) Spanish farmers. The by far most often mentioned reasons for cropping pattern decision making were "profitability & stability", much less often other aspects like the need for crop rotation, soil characteristics, tradition, low water needs etc. In this article, we thus introduce a possibility that farmers tend to avoid risks (accounting for the wish for "stability"), which is also in line with the design of recent economic models addressing the situation in the UGB (Blanco, Varela-Ortega et al. 2007; Varela-Ortega, Simó et al. 2006).

A case specific additional aspect is that in the UGB many farmers take more groundwater than granted by formal rules. Thus on the one hand simply assuming that overexploitation can be avoided by imposing restrictions on water use and expecting all farmers always accept formal rules is misleading. On the other hand many farmers do follow formal rules. In order to incorporate this situation, this model considers motivations to comply with formal rules which are complementary to the risk of getting a penalty for non-compliance which is incorporated in profit maximization (control of water laws is however very limited due to problems of monitoring and control (Llamas and Martínez-Santos 2005), thus penalties play a minor role).

Another factor important for land-use changes in the UGB may be labour intensity of land-uses. Changes towards irrigation and especially suggested future changes towards horticultural crops imply higher labour-loads for farms. However, family farms which are mostly run with family labour have some natural limit on labour capacity. Indeed, historically, it can be observed empirically that the total labour force of holdings in Castilla La Mancha remained rather constant in the period 1989 to 2005 (FADN). However, in the UGB, big farms belong to land-owners considering the land as capital investment which are called "office farmers" by small farmers (Llamas and Martínez-Santos 2005) and whose labour force is not restricted to family members. For those farmers, constraints on the applied labour force may however still arise from other sources like the availability of skilled workers or from the organizational structure of a farm. Gomez, Carlos et al. (2008) present a simulation tool which was developed by the Economic Analysis Unit of the Water Directorate at the Ministry of the Environment of Spain to reveal the implicit multi-attribute objective function lying behind observed cropping decisions. This tool assumes that farmers try to reduce the management complexity involved with implementation of a cropping pattern and uses as proxy variables for management complexity the overall quantity of labour required and the family labour required (and one further variable). This implies that farmers opt for land-uses involving less labour. Based on these considerations, in this model the required labour force of a land-use can influence the respective utility and we investigate the implications for land-use changes.

4.2 Diffusion of innovations

A second strand of literature that appears to be of major relevance regarding land-use change relates to the diffusion of innovations. The literature on diffusion of innovations complements the above discussed works through focussing on the process of adoption in a population over time (in contrast to focussing on single farmers' decisions). The term diffusion as used in this literature describes the spreading of an innovation. This does not happen immediately but takes some time. It is empirically well established, that the process of diffusion (roughly) follows an S-shaped pattern: initially some "innovators" adopt the innovation independently. While the innovation spreads and is increasingly recognised and accepted, the process speeds up and finally slows down again, when approaching a saturation level of adoption (e.g. Rogers 1995). There are many approaches to explain this diffusion pattern, ranging from mere economic approaches explaining diffusion through preferences and changing market situations to approaches from the social sciences highlighting the interpersonal communication and psychological dimensions of innovation diffusion. Elaborated models of innovation diffusion exist, e.g. including peer networks and heterogeneity of innovativeness (more innovative actors are more open to adopt innovations and thus in general earlier in doing so) of potential adopters (e.g. Valente 1995). Such models have been incorporated in agent-based models of land-use change and innovation diffusion (Berger, Birner et al. 2007).

In the UGB around 17.000 farms exist. We consider this number high enough to integrate an aggregate description of diffusion processes only, in order to reduce data needs and model complexity. An aggregated description also relieves this study from finding empirical evidence for and keeping track of changing network constellations and farmers' innovativeness (related to age, eduction) over the considerably long time period of 40 years. The Bass-model is a diffusion-model on an aggregated scale originating from the marketing sciences (Bass 1969; Mahajan, Muller et al. 1990). Although it reduces the complexity of a diffusion process to a minimum, it is found to perform well for forecasting purposes. The Bass-Model suggests external (e.g. advertisement) and internal (e.g. word of mouth) influence on non-adopters as driving forces for diffusion. The internal influence increases with the number of adopters, i.e. the diffusion of an innovation is modelled as a self-reinforcing process that tends towards a final saturation level of adopters. In this study we adopt an implementation of the diffusion process similar to the Bass-model; the more wide-spread an innovation is, the higher the probability, that a farmer considers this innovation when pondering about future land-uses (see section 5, Box 3).

4.3 Path-dependency

Policy changes and diffusion processes affect farms having an individual history, thus farmers' response to policies and innovations is contingent to the specific situation of a farm. In short, decision making of single farms is path-dependent. Path-dependency means that current and future decisions are influenced by the history of this farm. It arises from a range of sources: for example, tree crops like vine and olives which are widespread in the UGB have life-times of up to several decades and cutting them at an early stage means loss of capital. On the other hand, planting vineyards or olives includes up to five years without yield. Therefore the area dedicated to tree crops can be expected to change only slowly, and decisions on planting or cutting trees are contingent to the age of trees and not easily reversed. Further, machinery and irrigation technology constitute investments that must be depreciated and constitute sunk costs (assuming that second-hand markets work on a suboptimal level). However, machinery and irrigation technology are not suitable for all types of crops and therefore previous investments limit the options of a farmer to change cropping pattern in the future (at least makes some options less attractive). Balmann, Odening et al. (1996) have shown that path-dependency can arise from the asynchronity of life-cycles of assets; i.e. at each point in time some sunk costs exist which favour following the current path when making new investments (which then constitute sunk costs at a later stage and so on). Finally, farmers have knowledge of planting certain crops but not on planting others and on using certain irrigation technology but not others. Adopting previously unused crops or technologies involves learning efforts and bears the risk of reduced yields during a period of learning.

In this model, path-dependency is considered in the following ways: individual farms build up stocks of irrigation technologies and accumulate knowledge on crops. Further, farmers explore potential future land-uses based on current land-uses and not from scratch. And finally farmers' decision among potential future land uses depends (amongst other things) on the "difference" of the respective land-use related to his current situation. This "difference" is a rough calculation of learning efforts and uncertainty with respect to innovations as well as investments necessary and sunk costs (see section 5, Box 4 for details).

5 Model description

The model used in this work addresses land-use change focussing on the farm level and using an agent-based modelling approach. It explains an actor's behaviour as depending on this actor's characteristics, namely a farmer's priorities (having a high gross margin, having low risk, having low labour loads, staying legal), the size of the farm, the accumulated stock of irrigation technology and a farmer's knowledge (see Box 1). Those characteristics unfold their significance in the context in which the actor acts. This context comprises options and rules and is identical for all actors (see Box 2).

Using this concept it follows that in this model land-use change is considered as emergent outcome of (a combination of) change in options available, in rules advising and penalizing choices of options and in actors' individual characteristics. Innovation diffusion and path-dependency influence process dynamics.

Box 1: Actors' characteristics

Priorities

As outlined in the discussion in section 2, the model implements profit maximization, the minimization of risk, appropriateness of the quantity of labour required and a motivation to stay legal (see Box 2 for related options' characteristics and Box 5 for details of influence on utility).

Size of farm

The majority of farms in the UGB are small, having less than 20 ha. However, there are comparably few but very big farms (more than 100ha). In this model, five size classes are considered to capture this diversity: very small (4 ha), small (8 ha), medium1 (32 ha), medium2 (70 ha) and big (150 ha) (see table 4 in section 6 for more details).

Family labour

Farms are run with a certain amount of family labour. Family labour is considered available unpaid and is hence not included in the calculation of gross margin.

Stock of irrigation technology

The stock of irrigation technology of a farmer is represented on the one hand as area which this farmer can irrigate using a specific technology (sprinkler, drip) and on the other hand as available pumping capacity in m^3 of water (representing the number and capacity of wells owned by this farmer). This stock increases if a farmer chooses a land-use patterns whose area of a technology surmounts the respective current stock and / or whose water needs exceeds the current pumping capacity. The stock does not decrease.

Knowledge on crops and technologies

Farmers acquire knowledge by planting crops and using technologies. Knowledge is represented as asymptotic learning process in which skills increase each year a crop or technology is part of a farmer's land-use pattern. Initially farmers have some skills regarding the crops they plant when the simulation is started and additionally all farmers have perfect skills on rainfed cropping (being one "irrigation technology") and fallow land (set-aside).

Box 2: Context

Options

Options are combinations of crops and irrigation technologies (e.g. "rainfed vineyard" or "drip irrigated paprika"). They are basic building blocks for farmers' land-use patterns. When utilized by a farmer, options are related to an associated area, forming a "land use" (e.g. 20 ha of irrigated vineyard). A set of such "land uses" then forms a farmer's "land-use pattern". The land-use pattern is the unit that then is used to calculate outcomes (gross margin, water used, etc.). In this model, nine different types of crops and four types of irrigation are distinguished; resulting in a total amount of 23 options (not all combinations of crop and technology are feasible). Options are characterised by prices, yields, direct costs (fertilizer, seeds, etc.), and by the labour and water needed per ha (labour needs per ha decrease with the size of area dedicated to a crop due to increasing efficiency). Costs per labour unit and for pumping of water are also considered and assumed being the same for all options and actors.

Further, options and land-use patterns are characterised by an associated risk. "Risk" here refers to variability of gross margin due to short-term fluctuations of prices for products and inputs as well as variability of yields (due to weather conditions, pests etc.). In the model, risk is conceptualized as the standard deviation of total income (income from production + income from subsidies) related to expected gross margin (total income-costs; the cost side of production is assumed non-variable). Irrigation reduces risk since it decreases variability of yields. Diversification also reduces risk. Options' attributes and calculation of risk are specified in the appendix.

Formal rules

Formal rules provide constraints and incentives for using options. The rules implemented are changing over time (see appendix for details of rule representation) and comprise pumping quotas, CAP prices for cereals and sunflower, CAP compensatory payments and the Agro-Environmental Programme (AEP). Rules in principle have two types of impacts: changing the profit of a land-use pattern through subsidies or penalties (see appendix) and rendering a land-use pattern legal or illegal, depending on the implicated amount of water used.

Water quotas were introduced in 1986 (modified and reduced in 1991) and render land-use patterns illegal that use more water than an actor specific quota which depends on an actor's farm size and on his irrigation needs in 1985. Prices for cereals and sunflower are decreased, once in the period 1992-1995 and then further between 1999 and 2002, reflecting price developments originating form CAP reforms. CAP compensatory payments (since 1992) provide subsidies per area dedicated to irrigated and non-irrigated cereals and sunflower as well as set-aside land, and introduce an obligatory minimum set-aside area. The AEP is a voluntary programme, providing compensatory payments for reduced water consumption in comparison to a baseline amount. Farmers can choose between three options: 50%, 70% or 100% reduction, payments increasing for higher reductions. In its first phase (1993-2002), the baseline amount of water was independent from farm size. In the second phase (2003 onwards), the baseline amount of water was adapted to the pumping quotas and compensatory payments were decreasing with farm size.

The way farmers derive next year's land-use patterns is essentially at the heart of this model since here all variables (a farmer's characteristics, context, this year's land-use) come together and all model output is derived from the sequence of farmers' land-use patterns. The literature contains a wide range of models of farmer decision making as outlined in the introduction. It is beyond the scope of this article to review and discuss the various approaches and we refer the interested reader to the respective comparative literature (e.g. Schreinemachers and Berger 2006; Edwards-Jones 2006; Jackson, Quadus et al. 2006; Austin, Deary et al. 1996; Garforth and Rehman 2006; Mendola 2007; Janssen and van Ittersum 2007; Payraudeau and van der Werf 2005). Parker, Manson et al. (2003) identify the choice of agent rationality as one of the key challenges for designing an ABM. Hare and Pahl-Wostl (2001) have shown that the choice of different representations of agent rationality influences model results to a much larger extent than uncertainty in environmental data. Our representation of decision making is therefore first of all motivated by the goal to develop a modular approach that allows studying influences of the various factors identified in section 4 but also of impacts of variation of the implementation, i.e. of underlying assumptions with respect to different aspects of farmers' decision making. This article presents the overall model structure, the modular decision-making algorithm and a set of simulation results obtained from the first realised model implementation. Hence it does not incorporate an evaluation of the effects of changing deep assumptions but this is left to future work.

The process through which in this model farmers derive their land-use patterns is described in Box 3. In brief, it comprises the following steps: 1) a set of considered options is identified, including only those options a farmer has used before and some others, which are randomly chosen based on their spread; 2) a set of potential future land-use patterns is created by varying the current year's land-use pattern, 3) land-use patterns which are too different from the current year's land-use pattern are discarded; 4) consequences arising from formal rules are evaluated for each of the remaining patterns; 5) the utility-maximizing land-use pattern is selected (regarding this farmer's priorities and consequences from rules).

The basic modular structure of the algorithm facilitates easy variation of assumptions. For example, the implementation of selection of "considered options" in the first step relates to assumptions on information farmers have. Here, different assumptions can be compared, for example that farmers have perfect information (all options are considered) and that farmers do mostly observe the local situation (the more widespread an option, the more likely it will be observed and considered). Another example is the choice among land-use patterns in step five. Through variation in this step, e.g. the effect of satisfycing behaviour, of utilization of heuristics for decision making and of utility maximization can be explored and compared.

With regards to this exploration of alternative implementations, the creation of a discrete set of potential future land-use patterns in step two is considered useful. A wide range of especially heuristic approaches is restricted to dealing with discrete option sets (Jungermann, Pfister et al. 2005; Payne and Bettman 2001). Optimization can still be approximated through developing big sets of potential future land-use patterns in step two combined with maximization of utility in step five[3].

In this model, multiple criteria are compared and related by a farmer when deciding on next year's land-use pattern: gross margin, risk, labour load, legality. The implementation presented here rests on the assumption that farmers can invest time to think about this decision and thus incorporate all dimensions in their decision (instead of e.g. using a lexicographic heuristic considering only the most important dimension). A utility function approach is chosen. The utility $U(p_i)$ of a land-use pattern p_i is calculated using a Cobb-Douglas type of function as described in Box 5. This approach involves multiplication of the different attribute values what is convenient because it renders normalization of the attribute metrics unnecessary. Further, when multiplied, very low values on one attribute can not be so easily compensated on other attributes which seems intuitive regarding farmers (e.g. very low gross margin can rarely be compensated completely by very low risk).

The model runs in steps of one year. Each year, each farmer chooses a land-use pattern as explained in Boxes 3-5. The development of crop patterns, the usage of irrigation technology and the amount of ground-water used are outcomes of model runs which can be compared to empirical developments.

[3] In praxis, this is limited through contraints of time and computer resources. In the model runs shown throughout this article, we generate in step 2 1000 land-use patterns for each farmer in each year.

Box 3: Steps in the decision making process

1) Considered options: Out of the set of all options, a farmer *f* considers (only) those options that are combinations of crops and technologies both known to *f*. Further, unknown options are randomly considered, the probability increasing with usage of an option by other farmers, what induces a self-reinforcing diffusion process.

2) Considered patterns: Based on *f*'s land-use-pattern in the previous step p_0, a set of "considered patterns" p_i is developed. How the set of options considered in a decision making situation is generated in human minds is a field which is under-researched (Jungermann, Pfister et al. 2005) and we are not aware of any prevalent model for this step. In this model, a p_i is created through (randomly) iterating three basic operations on p_0 several times (the original p_0 is also considered further): a) add one considered option which is not yet part of this pattern and associate some area to it, forming a new land-use. The respective area is subtracted from a random other land-use lu_i. The new land-use has a size which is randomly chosen in [0, size(lu_i)]. b) Remove one land-use (if not the last), the respective area is added to a random other land-use, c) re-scale two land-uses: exchange some random area between two land-uses.

3) Discard too different land-use patterns: All the potential land-use patterns are checked for their distances to *f*'s current land-use pattern. These distances are explained in detail in Box 4 and comprise a) skills: uncertainty and learning efforts associated with a change in the area of land-uses (especially implementation of new crops and technologies) and b) capital: investments necessary and capital loss arising from the change in the area of land-uses. Both distances depend on the history of this farm; hence they capture the aspect of path-dependency on the farm level. For each land-use pattern p_i, *f* keeps p_i for further consideration randomly with a probability $p = (1\text{-}d)^{\alpha}$. This random filtering is done for both types of distances d_s (skills) and d_c (capital), α_s and α_c being respective parameters that can be adjusted to explore the influence on model behaviour. That is, those patterns that are "close" enough to *f*'s current land-use in both regards are likely kept for further consideration while more distant p_i are likely discarded.

Furthermore, all land-use patterns which comprise more than five different crops or more than seven different land-uses are discarded. This avoids computational problems arising from immense recursion in step 6. It is in line with empirical farm types identified by Varela-Ortega, Blanco et al. (2006) for the UGB. Note that p_0 is always kept in this step.

4) Rule application: Rules are applied, i.e. consequences (subsidies, penalties, legality) arising from choice of a potential new land-use pattern p_i are calculated. The AEP, a voluntary programme, is considered in the way that the highest available level of compensation is chosen (note that the land-use pattern is fixed in this step, so this does not involve trade-offs but simply taking the best, assuming that higher compensatory payments are considered better).

5) Utility maximization: The utility of all remaining patterns is calculated, utilizing *f*'s priorities regarding profit, risk, labour load and staying legal. This is elaborated in Box 5. The land-use pattern having the highest utility is selected to be implemented (we assume constant prices except for policy changes (see Box 2) and that farmers have perfect knowledge on respective prices, including changes through policies). Note that *f* will only shift to a pattern p_i with $i \neq 0$ if p_i's utility is higher than that of p_0.

(6) Refinement): The selected land-use pattern is refined. Options with marginal areas (marginal areas are considered those which are < 10% of farm size and at the same time < 1 ha) are deleted and the respective areas are shifted to other options. A set of refined pattern is developed containing all possibilities of re-distributing marginal areas and also the original pattern including marginal areas. Each of these refined land-use patterns goes again through steps 4 and 5. This step is conducted to avoid model artefacts like patches of very small land-uses due to random generation of pattern in step 2.

Box 4: Distances

For sake of simplicity, in this model, distances between crops are specified only for crop classes (COP = {traditional cereals, high-yield cereals, sunflower}, OFC (other field crops) = {sugarbeet}, horticultural crops = {melons, garlic, paprika}, tree crops = {vineyards, olives}.

Limited experience $d_s(f,p_i)$: The implementation of new crops (or irrigation technologies) and the extension of areas of crops (technologies) with which a farmer has limited experience is laden with uncertainty and involves learning efforts on the farmer's side. The distance representing this depends on the farmer's knowledge and prior experience (skills) and is assumed to increase with the area dedicated to the new crop (or technology). Farmers' skills are represented as values in [0,1] for each crop (technology). Uncertainty related to the extension of crops (technologies) being part of p_0 is computed as sum of areas of extensions multiplied with respective lack of experience (=1-skill). The part related to implementing new crops (technologies) depend on the distance to crops (technologies) this farmer knows already about and this farmer's respective skills. Distances are specified in matrices attaching a number in [0,1] to each pair of crop classes and technologies (see appendix). The sum of lack of experience regarding all new crops (technologies) in p_i weighted by the respective area is added to $d_s(f,p_i)$. A factor w_{tech} can be used to adjust the influence of irrigation technology related experience. The result is divided by the size of the farm.

Change in area of land-uses $d_c(p_0,p_i)$: Change in the area of crops (technologies) entails investments (new assets required) and sunk costs (unused assets, trees cut etc.). This factor is specific for the type of exchanged options, but independent from a farmer's experience and is assumed to increase with the area affected. A matrix specifies the distance between crop classes regarding the re-usability of assets as numbers in [0,1] (see appendix). The re-allocation of crop areas from p_0 to p_i is computed in the most efficient way regarding those distances. The crop specific part of $d_c(p_0,p_i)$ is then computed as sum of reallocated areas times respective specific distances. The part of d_c related to irrigation technology is computed as follows: the absolute values of areas irrigable with sprinkler and drip technology of p_0 and p_i are calculated and weighted (the absolute value is taken to represent unused assets if the area in p_0 is bigger than in p_i and necessary investments in the opposite case). The sum of both is normalized using the farm size. The absolute value of extracted amount of water (representing pumping capacity of wells) in p_0 minus that in p_i is calculated, weighted, normalized by the maximum extraction (=using the most water intensive option on the whole farm) and added to d_c. d_c is finally modulated by a random factor r representing varying situations regarding the age of assets, prices for used assets, interest rates, etc. r is modelled as normally distributed number to represent the accumulated effect of several independent factors.

(The computation of these distances is described in greater detail in the appendix.)

Box 5: Utility

$U(pi) = G(g(p_i))*R(r(p_i))*W(w(p_i))*L(l(p_i))$

G: function of the influence of gross margin $g(p_i)$

R: function of the influence of risk $r(p_i)$

W: function of the influence of labour (work) load $w(p_i)$

L: function of the influence of staying legal $l(p_i))$

$G(g) = g^{\gamma}$

$0<\gamma<=1$ is a parameter representing decreasing marginal utility of gross margin (for $\gamma<1$).

$$W(w) = Max[0, Min(1, (1 - \frac{w - w_f}{\kappa - w_f})^{\beta})]$$

w is the amount of labour needed for a land-use pattern, κ sets an upper limit of the labour load that can be handled by a farmer f and w_f is the available family labour (it is $\kappa \geq w_f$). β determines the shape of $W(w)$. Note that if $w< w_f$ then $W(w)=1$ and if $w> \kappa$ then $W(w)=0$.

$$R(r) = (1-r)^{\rho}$$

The values of risk r associated with a land-use pattern as calculated in the model are in [0.0,1.0]. ρ determines the shape of utility regarding r.

$$L(l) = Max(l, 0.5^{\lambda})$$

Being legal is binary: l *e {0 = illegal,1 =legal}*. If $l=1$ (legal behaviour) $L(l)=1$, thus utility is not reduced. If $l=0$ (illegal behaviour), λ varies the impact of illegal behaviour on utility.

In total the utility function is hence:

$$U(p_i) = g^{\gamma} \cdot (1-r)^{\rho} \cdot Max(0, Min(1,1 - \frac{w - w_f}{\kappa - w_f})^{\beta})) \cdot Max(l, 0.5^{\lambda})$$

6 Simulation experiments

In the experiments reported in the following, options and (changing) policies are the same for all model runs (see above and appendix for details). The model is initialized with farmers planting traditional crops. There is specialisation on vineyards or olives (mostly *very small*, *small* and *medium1* farmers) as well as specialisation on cereals (mostly *medium2* and *big* farmers). Some mixed farms of all sizes are also considered (having vineyards, olives and cereals) (see 6.2 for specific information). Each run reported is an average of ten simulation runs with identical parameters but different random number sequences. In order to reduce computation time, simulations have been executed with 100 farmers per size class and aggregated results are extrapolated[4].

6.1 Exploration of effects of factors included in the model

The model facilitates exploration of assumptions of the importance of different factors through altering the parameters that determine their influence: α_s (skills), α_c (investments and sunk costs), κ, β (influence of work load), γ (gross margin), λ (staying legal), ρ (risk) (see also Boxes 3 - 5 and table 2 below). In order to convey an understanding of the effects of those parameters and of meaningful parameter values, this section briefly reports on simulations in which each parameter alone is explored before the following sections report on more elaborate simulations. Initialization of farmers is as described below in table 4 but without differentiating between farmer types (all farms are assumed to have 1 AWU of family labour and identical parameter values).

The literature on farmers' behaviour (see section 2.2) clearly identifies that profit is a major objective of farmers (in western developed countries). This rather undoubted finding constitutes a baseline for all simulations: we assume $\gamma>0$, i.e. increasing gross margin increases farmers' utility. When zero relevance is attached to all farmers' priorities except gross margin and no barriers to change between land-use patterns are assumed, then, as can be expected, this model generates a diffusion of those land uses which maximize gross margin. In accordance with figure 2 those are drip irrigated garlic for smaller farms and drip irrigated melons for bigger farms. The diffusion process takes around 15 years. However, these results disagree very much with empirical data which show a dominance of cereals and vineyards (cf. table 1 and figure 3 below).

Table 2 summarizes how single parameters influence simulation results. All simulations reproduce a transition from rainfed to irrigated agriculture as observed in the MOA. Indeed for a big part of the analysed parameter space, this model generates even stronger change than empirically observed, namely a strong change-over from vineyards and cereals to horticultural crops. The main driver behind the transition is the increase in gross margin possible through irrigation. This increase is considerably stronger if farmers also change to horticultural crops (simultaneously with or subsequent to introducing irrigation; cf. figure 2). An interesting question is what has prevented such a switch to

[4] i.e. each of the 100 model farmers of size *very small* represents 80 real farmers (cf. table 4 in section 6.2) and consequently land-uses of this farmer are multiplied by 80 when computing aggregated model results like overall land-uses and water extractions. In contrast to this each of the *big* model farmers only represents 3 real farmers. 100 farmers per size class are considered an adequate compromise between limiting stochastic effects, computational effort and taking into account the different relevance of farms of different sizes for aggregated results.

horticultural crops in the real system. This is all the more interesting regarding future scenarios aiming at introducing larger shares of horticultural crops in the MOA.

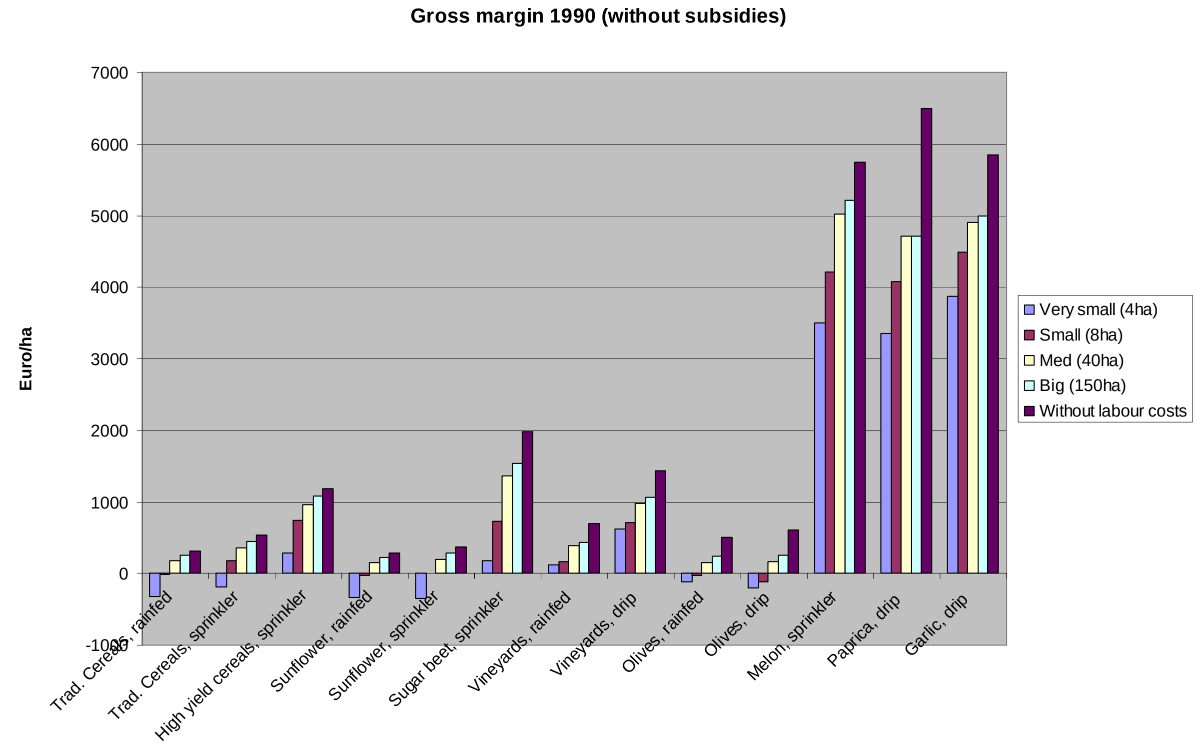

Figure 2: Gross margin of crops on different crop area sizes. Calculated from 1990 prices, yields, variable costs, labour costs, water pumping costs, without subsidies (all data as used in this model, see appendix).

According to the model, risk aversion is not sufficient to explain dominance of vineyards and cereals. The potential profit through planting horticultural crops provides (too) strong incentives and furthermore risk can be mitigated to a large extent through diversification. Very strong risk aversion must be assumed to "enforce" dominance of cereals and vineyards via the risk parameter (which however leads to non-plausible behaviour on the micro-level, see table 2).

Barriers due to limited skills and capital (α_c, α_s) slow down the changeover to horticultural crops but do not prevent it. In this model, barriers do not prevent farmers from starting out with small areas of horticultural crops, learning how to farm them and extending the land-uses slowly, probably waiting for favourable boundary conditions. Planting only small areas of a crop entails reduced economies of scale (for this and complementary crops), however, given the high gross margins of horticultural crops, overall gross margin still increases even when planting some small area of horticultural crops only.

Regarding restrictions on water use, the simulation results show that horticultural crops dominate and cereals vanish completely, even if no farmer acts illegally. On small farms, water is sufficient for horticultural crops if some part of the farm is left fallow or planted with rainfed crops (this is true only if farmers have irrigated already before 1985 so they could claim water rights). On big farms, planting a small area of horticultural crops complemented by larger areas of rainfed vineyards or olives makes a better strategy (regarding gross margin) than irrigated cereals.

Restrictions on labour capacity provide the only[5] explanation for the dominance of cereals on large farms. However, on small farms, planting horticultural crops is superior to vineyards. We conclude from this exploration of single parameters that no single parameter of this model is able to explain the empirically observed persistence of cereals and vineyards.

6.2 Farm types

In the next step we explore parameter combinations. The parameter space is too vast and simulations take too long to undertake a full scan of the parameter space via a Monte-Carlo-Analysis[6]. Further, not all possible parameter combinations are also meaningful. A random search in parameter space as conducted by a Monte Carlo Analysis may produce misleading results. Instead, the exploration of the parameter space presented here is guided by case-specific empirical knowledge about the types of farmers prominent in the UGB. We identify three types of farmers based on Hill (1993), Llamas and Martínez-Santos (2005) and Eurostat data:

- **Part-time farm**: the farmer and his family do not make a living out of farming but have income mostly from an off-farm job. The farm is almost exclusively run with family labour input in the residual time.
- **Family farm**: the farmer and his family live from farm income. The farm is run mostly with family labour (family labour is more than 50% of total labour force).
- **Business oriented farm**: the main goal of the farm business is to make profit. The farm is run mostly with non-family labour input.

We use these types to identify meaningful clusters of parameter values. Table 3 shows how the decision making of the various types differs and how this is translated into parameter values of this model. Table 4 relates the farm types to farm sizes and compares the model population to empirical estimates. Table 5 shows the operationalization of (initial) specializations of farmers and - based on table 4 and 5 - table 6 compares the initial model crop distribution to empirical estimates.

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[5] In this model with parameters set as described in table 2.

[6] One simulation run takes around 15-30 minutes on a standard desktop PC. We tried an exploration of the parameter space using two values for each parameter shown in table 2 (not including β but γ instead). In total this leads to $2^6 = 64$ scenarios. Each scenario was simulated five times, i.e. in total 320 runs. This exercise remained however mostly inconclusive and is thus not reported here. More extensive explorations of the parameter space are not feasible given limitations of time and computer resources.

Param.	Description	Effect on simulations
ρ	Determines the impact of risk on utility. The higher ρ, the stronger risk decreases utility. Risk refers to variability of gross margin due to short-term fluctuations of prices for products and inputs as well as variability of yields.	The following simulations have been performed: ρ ϵ {0.25,0.5,1,2,3,5,10,15,25,50} ρ =0.25 shows no difference to ρ =0. ρ ϵ [0.5,10]: farmers plant crops with highest gross margin and use diversification among those to reduce risk. The bigger the farm, the higher the effect of ρ (e.g. *big* farmers add garlic as second crop for ρ =1.0 and add paprika as third crop for ρ≥2.0 while *small* farmers add melons as second crop only for ρ>5.0). An explanation for size dependent responses are economies of scale whose non-linear shapes imply stronger effects when partitioning smaller areas compared to bigger ones. ρ≥15: farmers strongly diversify their crops (up to 5 different crops) including less profitable but less risky crops (cereals). Farmers adapt land-uses to make use of subsidies to further reduce risk. Although effects on the macro-scale seem plausible, behaviour of individual farms on the micro-level is erratic and counter-intuitive, e.g. a drop of more than 50% in gross margin is accepted to reduce risk less than 10%.
λ	λ varies the impact of illegal behaviour on utility. The higher λ, the stronger utility is reduced. This parameter models complementary motivations to cost considerations to stay on the legal side.	The following simulations have been performed: λ ϵ {0.5,1,2,3,5} All simulations are similar to the simulation with λ=0.0 until the introduction of the water law in 1985 (before that the only regulation is that vineyards may not be irrigated but in these simulations vineyards do not play a role anyway). λ ϵ [0.5,1]: farmers reduce land-use and leave residual land fallow in order to comply with water law. But after further reduction of legal water (pumping quotas) all farmers except *very small* ones switch back to previous patterns (the pumping quotas do not comprise further reduction for *very small* farms). This switching back occurs because loss of gross margin when complying with pumping quotas would affect utility stronger than becoming illegal. Maintaining reduced water use according to the water law (but not complying with pumping quotas) does not make sense since being legal is binary. λ≥2: farmers stay completely legal (with some exceptions in transitory adaptation phases, e.g. shortly after introduction of pumping quotas; for λ=2 big farmers switch back to being illegal as described above). *Medium1* and bigger farmers comply with pumping quotas through switching to mostly rainfed vineyards complemented by some melons. They join the AEP.
κ	κ represents the maximum labour force to which this farm is extendable. Hence κ also constitutes an upper limit for the labour load of	The following simulations have been performed: κ was increased from 1 to 9 in steps of 0.5; the related β is set to 1.0 (see below). *Very small* farmers are not affected at all. *Small* farmers are only affected for very low values of κ and only in the way that garlic area is somewhat reduced and complemented by fallow to reduce labour load. Bigger farms plant irrigated cereals but after cereal prices drop in the mid 1990s they stop irrigation but join the AEP (for low κ with rainfed cereals for somewhat higher κ with (small) areas of garlic (rest is fallow)). The shift in strategy from horticulture (+fallow) as observed without labour limit to the described strategy

	land-use patterns.	occurs for *medium1* farms for κ<= 2.5, for *medium2* farms for κ<=4.0 and for *big* farms for κ<=7.5.
β	β determines how utility drops with labour load in the range between a farm's family labour (no negative impact) and κ (utility = 0).	The following simulations have been performed: β ϵ {0.5,0.75,1.0,1.5,2.0}; κ was set to 5.0 since for high κ the effect of β can be expected to be most pronounced. β does not induce qualitatively new dynamics but produces results which are similar to reduced / increased κ; e.g. {κ=5 β=2} produces very similar results as {κ =4, β=1}. β is thus set to 1.0 in all following simulations.
λ_s	λ_s determines how frequently "distant" land-use patterns are discarded from further considerations. Higher λ_s lead to more frequent discarding. λ_s relates to land-use patterns' "distance" to a farmer in terms of this farmer's knowledge and prior experience (skills).	The following simulations have been performed: λ_s ϵ {1,2,3,5,10,15,20,25,30,50} λ_s ϵ [1, 10]: λ_s induces a delay in developments which is however clearly recognizable only for $\lambda_s \geq 5.0$. The attractor of the simulations is not changed but for $\lambda_s \geq 10$ diffusion of utility maximizing land-use patterns is delayed until after the simulation ends. On the micro-level changes between crops usually proceed over some few years, starting with a small area of the new crop which is then further increased. The delay induced by λ_s has to be interpreted carefully since it is dependent on the number of patterns generated in step 2 of the decision process (see Box 4): the higher the number of patterns generated, the faster farmers "find" land-use patterns which allow both, high utility and "testing" new crops / technologies. $\lambda_s \geq 15$: Simulations reach a stable (macro-level) mix of garlic, melons and paprika for the size classes *very small*, *small* and *medium1*. On the micro-level, individual farmers are however specialised on one crop only. The likely explanation is that switches between specialisations are (almost certainly) "filtered away" as too distant but intermediate land-use pattern featuring more than one crop are not chosen due to low(er) utility. For farms of size *medium2* and *big* the macro-level shows ongoing increase in garlic and melon area and an intermediate phase of much paprika.
λ_c	λ_c is similar to λ_s but relates to land-use patterns' "distance" to a farmer's current land-use pattern in terms of sunk costs and necessary investments.	The following simulations have been performed: λ_c ϵ {1,2,3,5,10,15,20,25,30,50} λ_c induces a delay in developments which is however clearly recognizable only for $\lambda_c \geq 10.0$. The higher λ_c, the more gradual shifts become on the micro-level (i.e. farmers increase / decrease some crop area over several years). The delay induced by λ_c has to be interpreted carefully (see λ_s). λ_c does not produce stable lock-ins to suboptimal options (as does λ_s) because it features a random factor which is most probably low sometime for the respective shift (hence the shift is only delayed, not prevented) . The higher the level of λ_c, the later individual runs converge because random differences arising in the initial "exploration phase" are maintained longer.

Table 2: Parameters and their effect on simulation results (all simulations performed with γ=1).

	Part – time	**Family farm**	**Business oriented**
Monetary profit	*Diminishing marginal utility of gross margin* Farming is mainly a "hobby"; farmer not dependent on farm income ($\gamma < 1.0$)	*Diminishing marginal utility of gross margin* Most important to secure some income but high profit is less important since the farm household has no structural requirement for profit ($\gamma < 1.0$)	*Linear influence of gross margin on utility* Profit is aspired, the higher the profit the better ($\gamma = 1.0$)
Risk	*Risk neutral* Farmer not dependent on farm income (ρ low)	*Risk averse* General finding from the literature: farmers are risk averse (ρ high)	*Risk averse* General finding from the literature: farmers are risk averse (ρ high)
Respect water law / pumping quotas	*Medium intrinsic motivation* Do not consider rightful that groundwater was transferred to public ownership but are not dependent on farm income. (λ medium)	*Low intrinsic motivation* Do not consider rightful that groundwater was transferred to public ownership; perceive it as their right to pump as they used to before 1985 (λ low)	*Medium intrinsic motivation* Politically active, need to maintain credibility. (λ medium or high)
Family labour (in AWU)[*]	0.4	1	0.4
Hiring of additional workers	*Very limited* To address peak times (e.g. harvest) only (κ very low)	*Limited* Up to amount of family labour (per definition used to differentiate types) (κ low)	*Yes* (κ high or very high)
Influence of sunk costs of human capital / learning efforts (skills)	*High* Low motivation to change business (α_s high)	*High* Farmers have a life-time of experience with "their" crop and style of farming (α_s medium or high)	*Low* Possibility to hire different workers with different skills, if required (α_s low or medium)
Influence of sunk costs (machinery, technology, trees) and necessary investments (capital)	*Low* Investments small (small farm size) and off-farm income available but low motivation to invest (α_c low or medium)	*High* Bad access to loans (α_c high)	*Low* Good access to loans (α_c low or medium)

Table 3: Heterogeneity of farm types regarding decision making.
** see appendix for sources of estimates.*

		% of all farms	part – time	family farm	business-oriented	% speciali-sation per farm size	% farms of this size (model)	Empirical estimates
very small		specialist COP	0	0	0	0.0	46.5	46.8
ha	4	specialist vine	15	16.5	0	67.7		
nr	8000	specialist olives	10	5	0	32.3		
area	32000 ha	mix	0	0	0	0.0		
	% of types of very small		53.8	46.2	0.0			
small		specialist COP	0	0	0	0.0	35	35.1
ha	8	specialist vine	5	16	0	60.0		
nr	6000	specialist olives	7	0	0	20.0		
area	48000 ha	mix	0	7	0	20.0		
	% of types of small		34.3	65.7	0.0			
medium1		specialist COP	0	0	0	0.0	12	11.7
ha	32	specialist vine	0	8	2	83.3		
nr	2000	specialist olives	0	0	0	0.0		
area	64000 ha	mix	0	2	0	16.7		
	% of types of medium1		0.0	83.3	16.7			
medium2		specialist COP	0	0	2	42.6	4.7	4.7
ha	70	specialist vine	0	0	2	42.6		
nr	800	specialist olives	0	0	0	0.0		
area	56000 ha	mix	0	0.7	0	14.9		
	% of types of medium2		0.0	14.9	85.1			
big		specialist COP	0	0	1.5	83.3	1.8	1.8
ha	150	specialist vine	0	0	0	0.0		
nr	300	specialist olives	0	0	0	0.0		
area of type	45000 ha	mix	0	0	0.3	16.7		
	% of types of big		0.0	0.0	100.0			
	types % of total		37.0	55.2	7.8			
		empirical estimates	37.1	54.8	8.1		Total area:	245.000 ha

Table 4: Distribution of farms according to sizes, types and crops planted (at model initialisation in 1960). Classification of farm sizes and respective numbers of farms according to Llamas and Martínez-Santos (2005) and Lopez-Gunn and Hernadez-Mora (2001). Empirical estimates for "% of farms of this size" computed from "nr" of farms of this type and total number of farms. For estimation of shares of types see appendix.

% of farm area	Specialist Vineyards	Specialist Olives	Specialist COP	Mix
Vineyards	80			20
Olives		80		10
Traditional Cereals			70	40
Fallow	20	20	30	30

Table 5: Operationalization of specializations (used in table 4)

	Model crop areas in % of total area	Empirical estimates
Vineyards	44.6	45
Olives	8.0	10
Cereals	23.4	20
Fallow	24.0	25

Table 6: Initial crop distribution (arising from table 4 and 5). For base of empirical estimates see appendix.

6.2.1 Simulation results of single types

We first ran simulations for each single type with all farmers of all sizes belonging to this type. For the analysis of results we focus on the areas of irrigated crops since this constitutes the base for associated groundwater extractions. Figure 3 hence shows the available empirical data to provide a base for this analysis. Table 7 provides an overview on the scenarios and figures 4-6 show the respective results including some parameter variations for those parameters we are most uncertain about for the respective type.

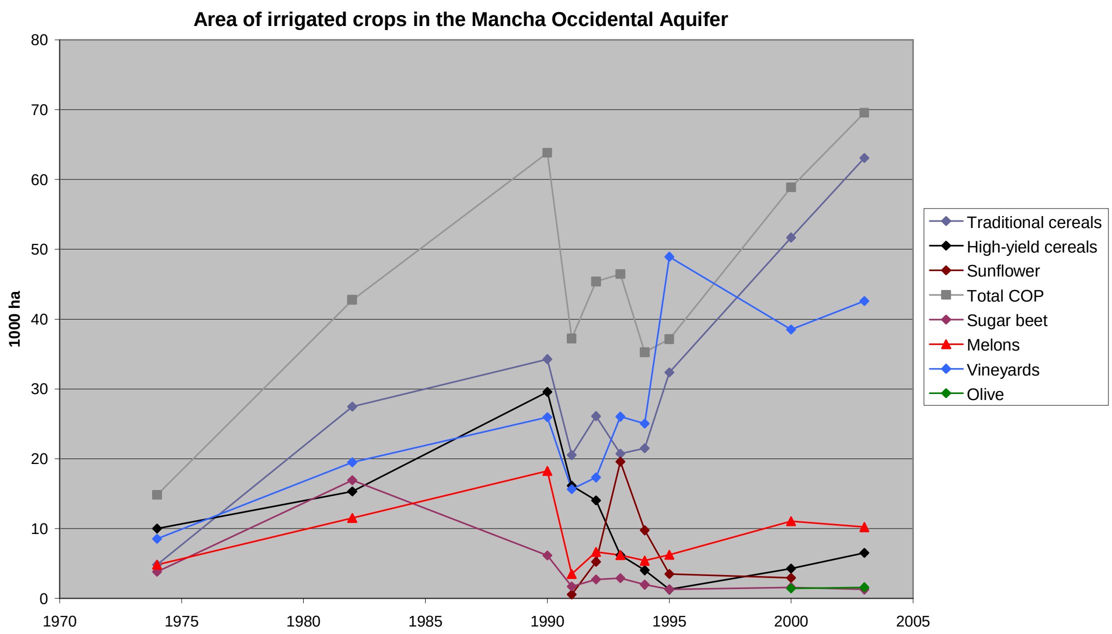

Figure 3: Area of irrigated crops in the MOA (Llamas and Martinez-Santos 2005).

	Family labour	γ	ρ	κ	λ	α_c	α_s
Business Farm	0.4	1.0	5.0	5.0	3.0	20.0	20.0
Family Farm	1.0	0.5	5.0	2.0	0.5	30.0	30.0
Part-time farm	0.4	0.5	2.0	0.6	3.0	20.0	50.0

Table 7: Operationalization of farm types

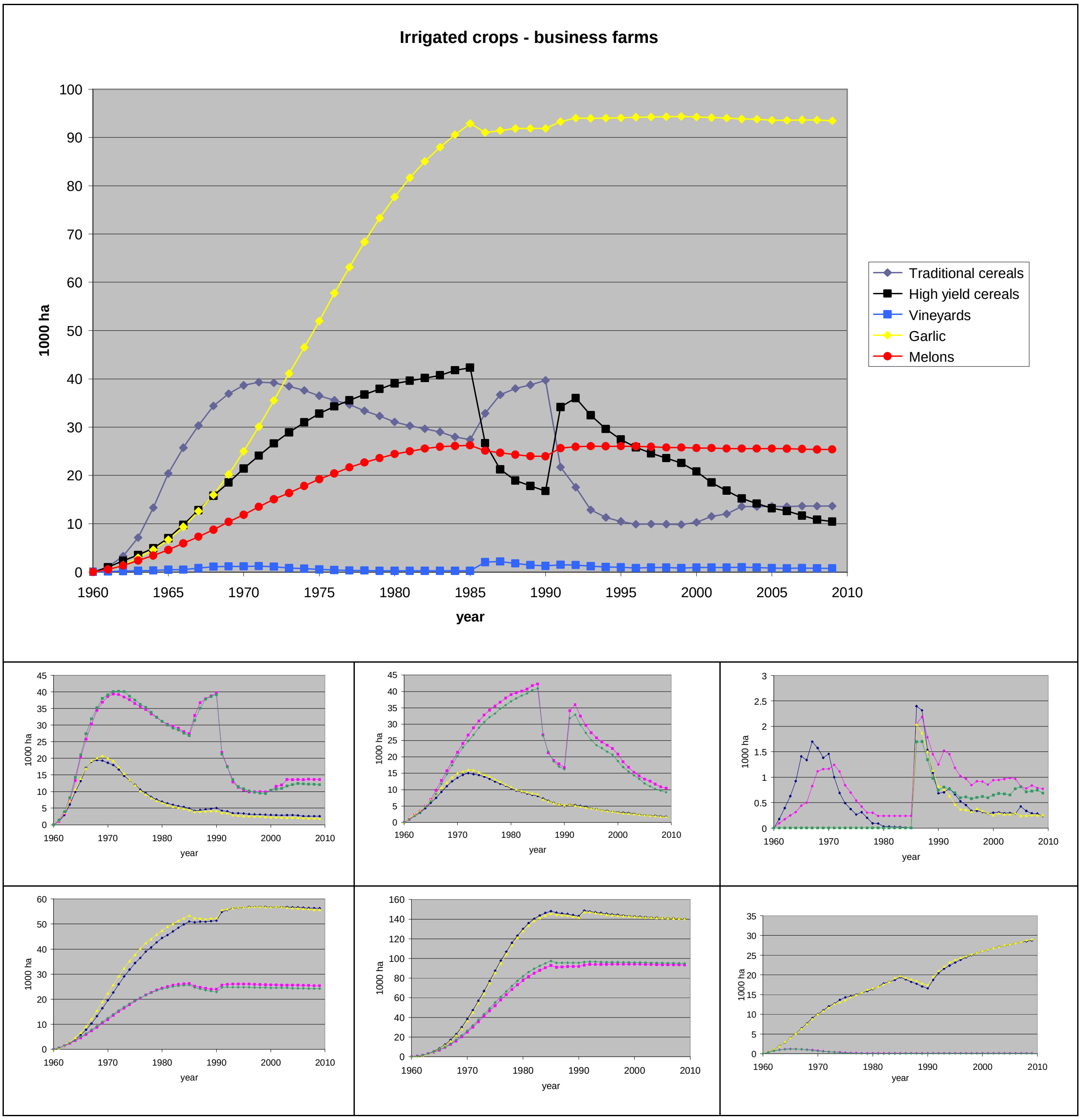

Figure 4: Irrigated crops for the scenario of business-oriented farms. The above figure shows all crops whose area comprises visibly more than 0ha for parameters γ = 1.0, ρ = 5.0, κ = 5.0, λ = 3.0, α_c = 20.0, α_s= 20.0. The small figures show single crops for parameter variations λ=3.0, κ=∞ (blue), λ=3.0, κ=5.0 (pink), λ=5.0, κ=5.0 (green) and λ=5.0, κ=∞ (yellow). Crops are (from left to right and top to down): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika.

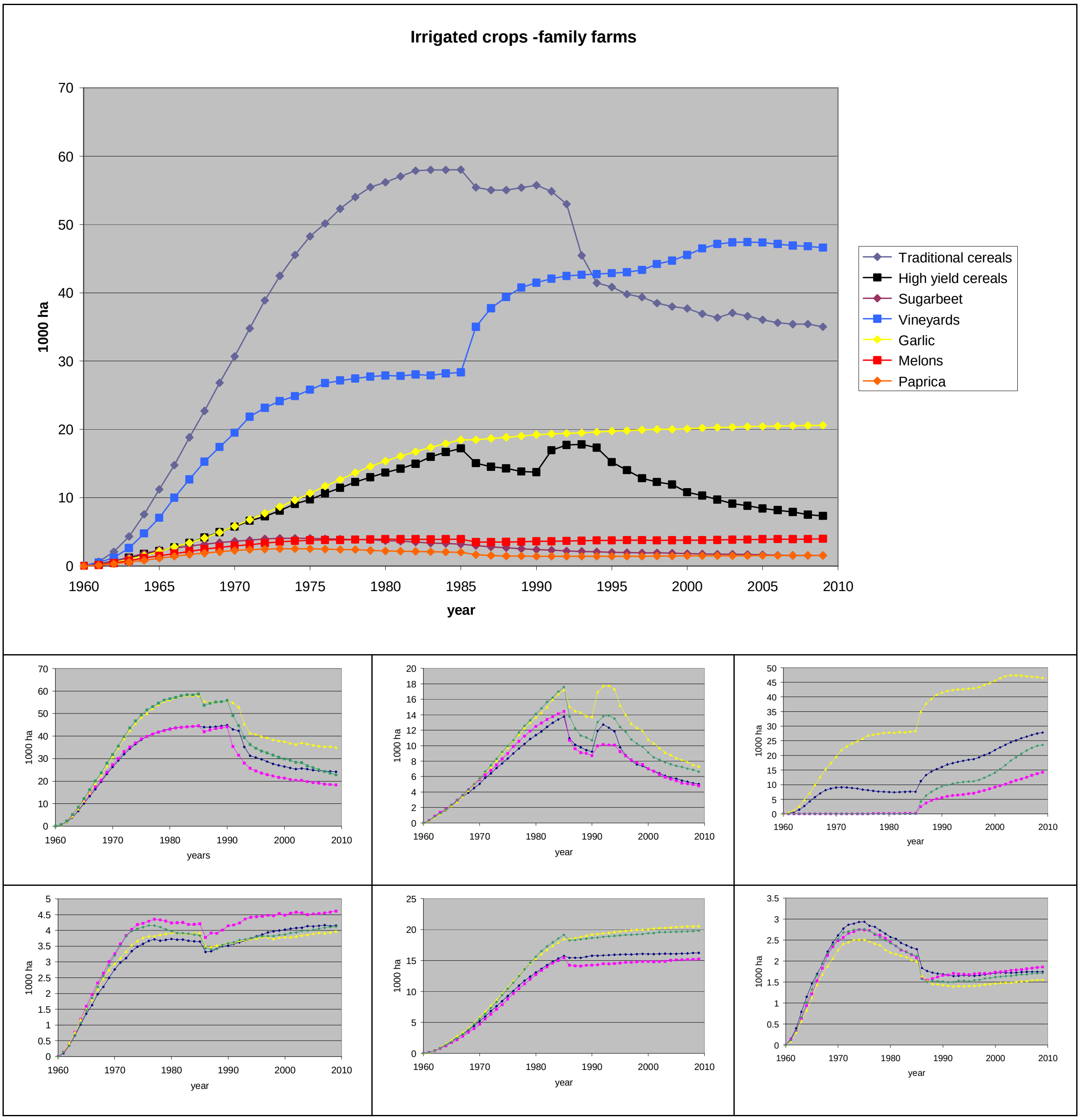

Figure 5: Irrigated crops for the scenario of family farms. The above figure shows all irrigated crops whose area comprises visibly more than 0ha for parameters $\gamma = 0.5$, $\rho = 5.0$, $\kappa = 2.0$, $\lambda = 0.5$, $\alpha_c = 30.0$, $\alpha_s = 30.0$. The small figures show single crops for parameter variations $\lambda=0.5$, $\kappa=1.5$ (blue), $\lambda=3.0$, $\kappa=1.5$ (pink), $\lambda=3.0$, $\kappa=2.0$ (green). $\lambda=0.5$, $\kappa=2.0$ (yellow). Crops are (from left to right and top to down): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika.

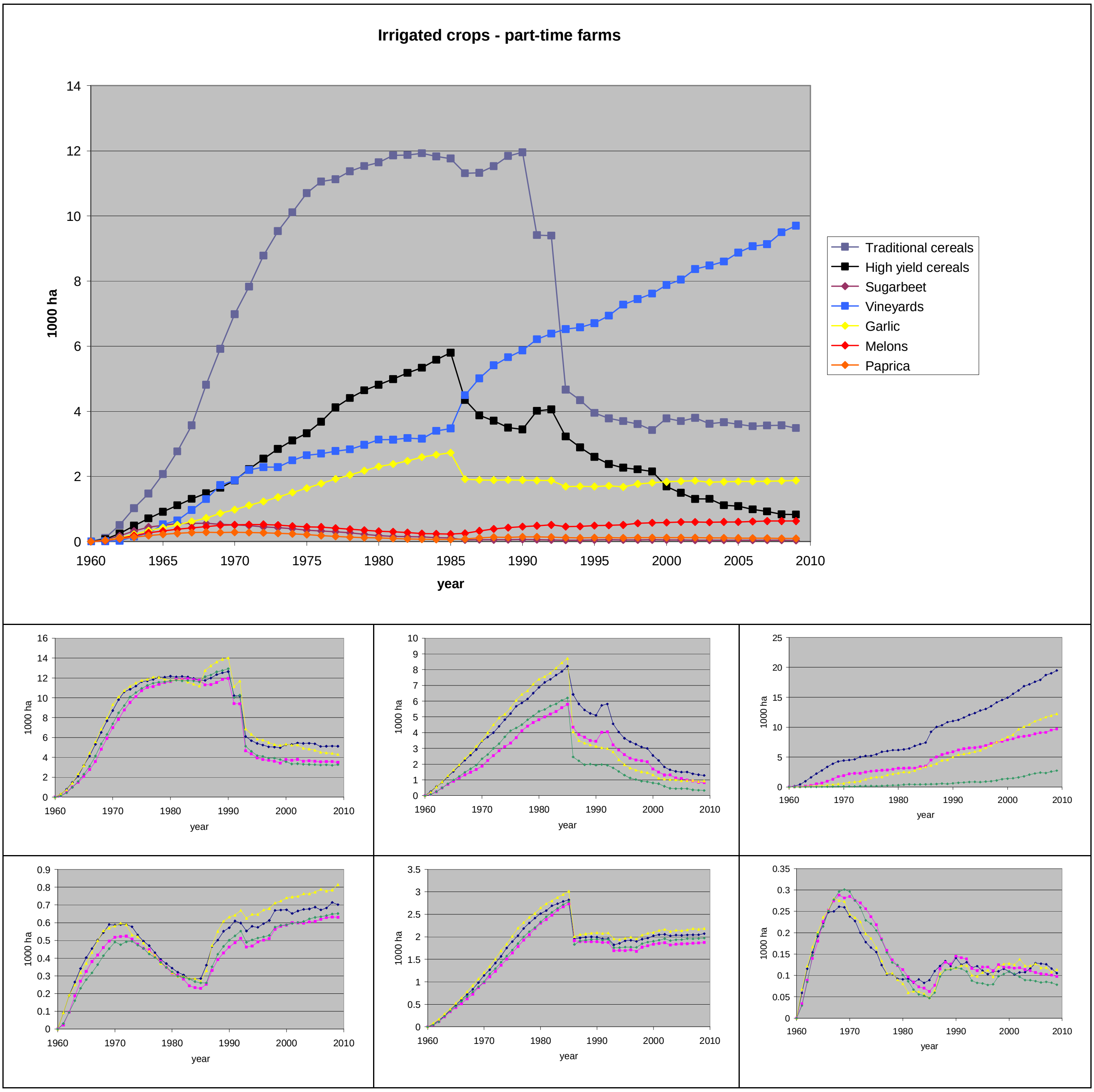

Figure 6: Irrigated crops for the scenario of part-time farms. The above figure shows all irrigated crops whose area comprises visibly more than 0ha for parameters γ=0.5, ρ=2.0, κ=0.6, λ = 0.5, α_c = 20.0, α_s= 50.0.
The small figures show single crops for parameter variations λ=0.5, α_s=20.0 (blue), λ=0.5, α_s=50.0 (pink), λ=3.0, α_s=50.0 (green). λ=3.0, α_s= 20.0 (yellow). Crops are (from left to right and top to down): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika.

Results show for business farms a considerable difference between κ=5 and $\kappa=\infty$ (figure 4): for κ=5 cereals play a somewhat stronger role while for $\kappa=\infty$ irrigated cereals are only a transient phenomenon and horticultural crops are the very dominant irrigated crops. An in-depth analysis[7] of simulations with $\kappa=5$ reveals that irrigated cerals are actually implemented on *big* and *medium2* farms which is in line with empirical findings. A limitation of the labour capacity of business-oriented farms below 5 AWU is also in line with empirical findings. Hill (1993) found an average of (only) 2.26 AWU for Spanish non-family farms[8] using FADN data. However, such an empirical observation does not explain why this is the case. A potential explanation is given in figure 7: regarding gross margin, cereals constitute a local optimum for low labour input on large farms. A considerable increase in labour input is required to actually increase gross-margin through a shift to horticulture. In this model, there is no barrier that prevents an immediate increase of a farms labour force from say 1 AWU to 4 AWU. In reality this might constitute considerable organisational problems. A slow change-over to higher labour capacity may be prevented since it is (at first) not accompanied by increasing but rather decreasing gross margin.

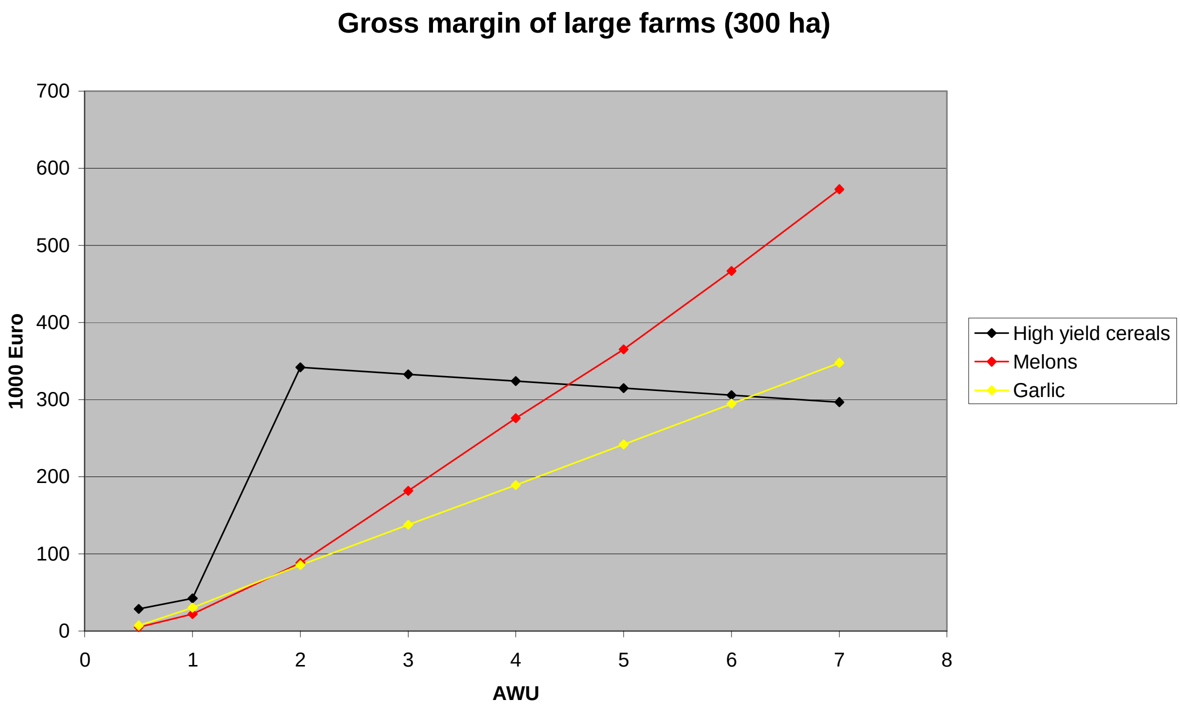

Figure 7: Gross margin of large farms over labour input. Gross margin is calculated for the maximum crop area possible considering limitations through the size of the farm and through the labour available (e.g. with 2 AWU high yield cereals can be planted on the whole 300 ha while melons and garlic can only be planted on ~17-18ha). For sake of clarity the farm size is chosen to be 300 ha. Farms of this size are not represented in the model but do exit in the MOA. The effect of a local lock-in holds for smaller farms but is less pronounced.

[7] Not shown in figures due to space limitations.

[8] In Hill's work these are all farms for which family labour makes less than 50% of the total labour force, i.e. what we call part-time farms are not included in Hill's non-family farms but only our business-oriented farms.

The scenario for family farms shows a balance between irrigated cereals, vineyards and horticultural crops and an amount of irrigated area which is closer to empirical observations than the scenario for business-oriented farms. The strongest variability arising from parameter variations exists regarding irrigated vineyards. Here, both parameters varied have strong influence. λ is decisive for irrgation of vineyards in the first half of the simulation. Only if λ is very low, farmers irrigate vineyards (which is in line with empirical findings). κ is decisive for the area of irrigated vineyards. An in-depth analysis reveals that on *medium1* and *medium2* farms the strong restriction of $\kappa=1.5$ makes it not reasonable to irrigate vineyards because the required labour can not be met. $\kappa=1.5$ is probably a too strong limitation.

The most prominent feature of the part-time farm scenario is the low overall extent of irrigated area. This is not too astonishing considering that even big farms have only ~0.5 AWU available, which is too little to run bigger farms. Part-time farms of size *medium1* or bigger are exceptional, if they exist at all in the MOA. It is hence reasonable to focus the analysis on smaller farms. Regarding very small and small farms, this scenario is outstanding regarding the persistence of rainfed vineyards and rainfed olives (not shown in figures). A persistence of rainfed vineyards and olives is in line with empirical findings (cf. appendix). However, given the comparably small overall area of part-time farms (~14% of total area) part-time farming can be only a partial explanation for the persistence of rainfed tree crops observed empirically.

6.2.2 Combination of types

The previous analysis shows that the different types of farmers identified and the according "logics" of production generate quite distinct patterns of land-use change. Therefore it is not reasonable to focus on one type alone but all the different types have to be considered. This section analyses results arising from simulations combining the three types as proposed in table 4. Figure 8a shows the area of irrigated crops. Unlike figures 4-6 it does not explicate irrigated areas of single crops since the parameters simulated do not induce interesting variations. Instead some more aggregated and some additional simulation results are presented which we use in the following to discuss the model's performance in light of empirical findings.

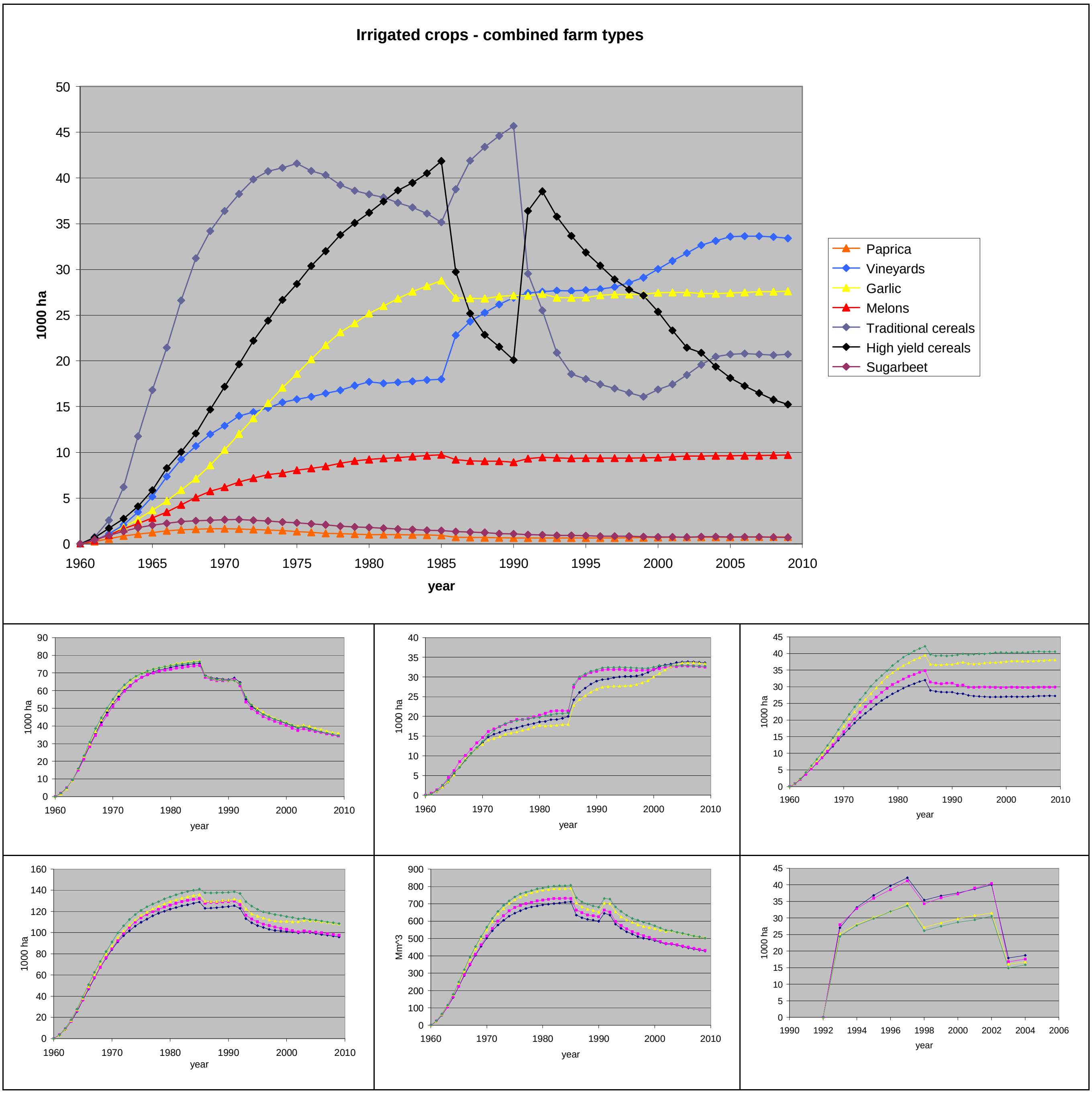

Figure 8a: The above figure shows irrigated crops for the scenario of combined farm types (parameter values as in table 7). The small figures show (from left to right and top to down): irrigated COP area (COP = traditional cereals + high yield cereals + sunflower), irrigated vineyards, irrigated horticulture (melons + garlic + paprika), total irrigated area, water extractions, area under AEP. Parameter variations are $\kappa_{business}$=4.0, κ_{family}=2.0 (blue), $\kappa_{business}$=4.0, κ_{family}=2.5 (pink), $\kappa_{business}$=5.0, κ_{family}=2.5 (green) and $\kappa_{business}$=5.0, κ_{family}=2.0 (yellow).

The total COP[9] area rises until 1985 to a similar level as observed empirically (cf. figure 3). The subsequent drop in irrigated COP area is underestimated by the model and the model does not capture the increase of irrigated COP area after 1995. On the disaggregated level, a prominent feature of empirical data is a peak of irrigated sunflower around 1993. This is not captured by the model but model results show an analogue short-term re-rise of high-yield cereals. Irrigated vineyards rise to an approximately similar level in the model and in empirical data. An intermediate drop of irrigated vineyards around 1990 is not captured by the model. Horticultural crops also rise to a similar level in the model and empirically. However, empirically only melons play a role while in the model the main share is garlic. Data on melons and garlic shows similar gross margin and labour intensity with garlic being somewhat superior for smaller farms. The observed difference could be explained through errors in data which artificially favour garlic over melons. A more significant shortcoming of the model is its inability to reproduce the empirical drop in the area of horticulture after 1990.

The total irrigated area and the water extractions (cf. figure 1 for empirical data) resemble the differences in areas of irrigated crops discussed above regarding COP and horticulture. The model does not reproduce a drop around 1985-1990 and a subsequent re-rise but simulation results instead show a slight decline. The area subscribed to the AEP may be an explanation for some of the observed differences. Empirical data shows a total area subscribed to the programme of around 80.000 ha in the time 1993-2002 and a strong drop in 2003 (Llamas and Martinez-Santos 2005). The model captures the drop but the total area is underestimated (~30.000 to 40.000 ha). Since joining the AEP requires reductions in abstractions and of the irrigated area, this shortcoming may explain some of the above differences. However, it does not provide an explanation for the drop of horticultural crops around 1990 (previous to the introduction of the AEP) which is not captured by the model. A drop in horticulture around 1990 can to a certain extent be reproduced but not fully explained when barriers due to sunk costs (i.e. α_c) are assumed to be very low for business-oriented farms but instead higher barriers due to limited skills are assumed. This is shown in figure 8b. Figure 8b further shows that this change in parameters also affects the drop in COP area after 1985 which resembles more closely empirial data than figure 8a. Consequently also the drop in total irrigated area and in the amount of water extracted is better captured. However, still a considerable amount of horticultural crops is maintained after 1990 (most of it on *medium2* sized business-oriented farms) and the increase in irrigated COP area after 1995 is not reproduced.

[9] COP is an abbreviation for cereals, oilseeds and proteins. In this model COP cover traditional cereals, high-yield cereals and sunflowers.

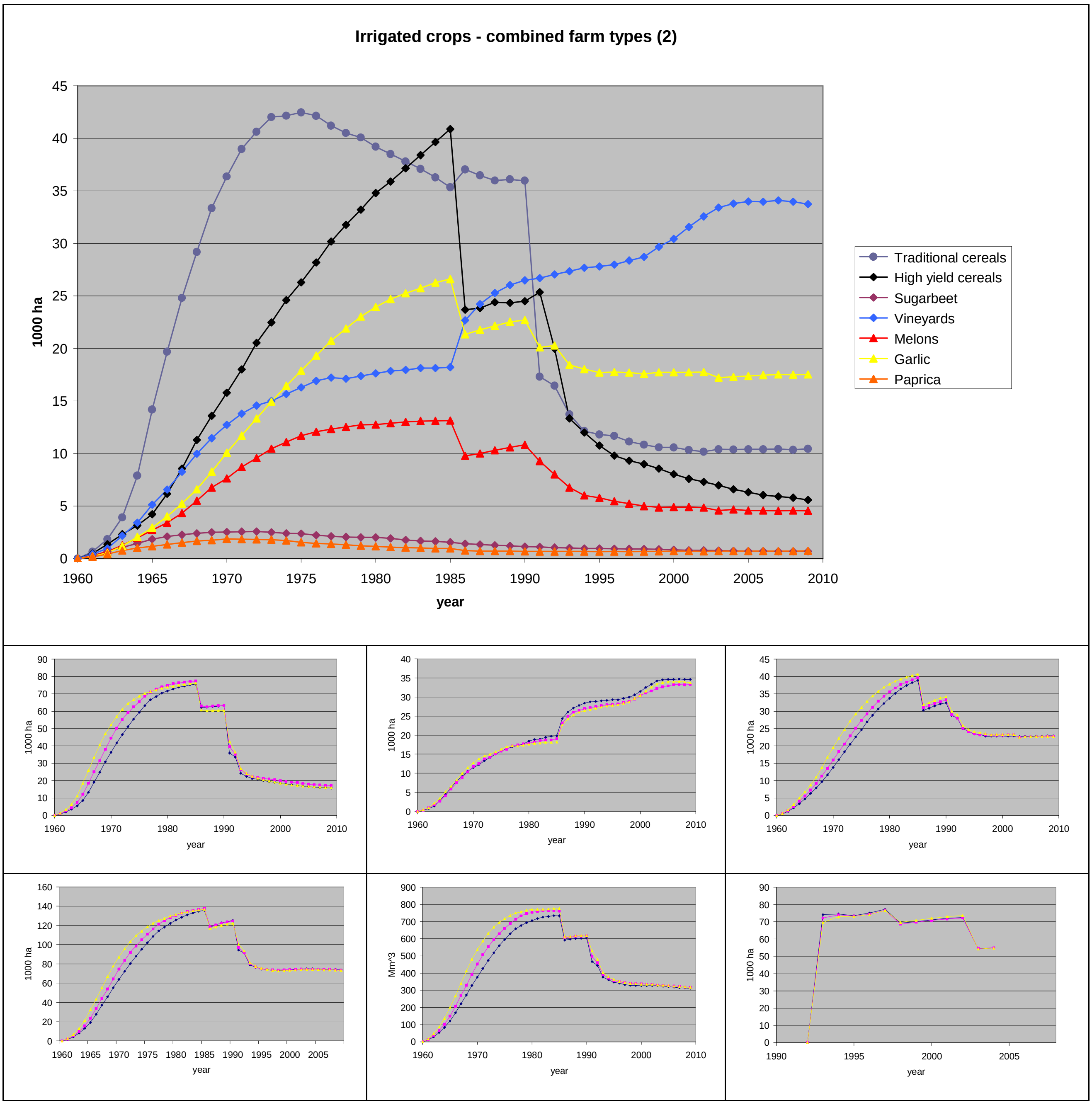

Figure 8b: The above figure shows irrigated crops for the scenario of combined farm types (parameter values as in table 7, except $\alpha_{c\ business}$=5, $\alpha_{s\ business}$=50).

The small figures show (from left to right and top to down): irrigated COP area (COP = traditional cereals + high yield cereals + sunflower), irrigated vineyards, irrigated horticulture (melons + garlic + paprika), total irrigated area, water extractions, area under AEP. Parameter variations are for business-oriented farms α_s=100.0 (blue), α_s=70.0 (pink), α_s=50.0 (yellow).

7 Discussion

7.1 Methodological considerations

In this model, farmers' choice of crops and technologies arises from a farm's history and attributes and from the context in which the farmer acts. Those attributes and also the context can change (partly endogenously), allowing history to unfold. This approach allows exploring those factors underlying land-use change which generate the observable sequence of land-use patterns. The model is flexible and complex enough to integrate, using a formal method, a set of factors simultaneously. Model building thus facilitates accounting for potential interactions among factors included, what can not easily be achieved with less formal methods (e.g. qualitative analysis). Nevertheless, the complexity of this model remains on a level that maintains transparency, i.e. simulation results can be traced back to underlying assumptions. This is considered important because it allows developing general lines of argument which are independent of the details of this model (see section 7.2.). Such reasoning can then flow into a debate without the need to understand the details of this model or the pros and cons of (agent-based) modelling in general. In this way, this modelling exercise enhances understanding of the mechanisms behind land-use change and provides insights that are potentially transferable from the studied case to future scenarios and to other regions facing similar problems.

This model is designed to explore the implications of a set of assumptions which are intractable without a simulation model due to the complexity of the topic. Selected simulations were performed including exploration of some parameter variations, guided through increasing understanding of the model behaviour. The parameter space of the model was explored step-wise, starting with single parameters and proceeding over parameter sets (farm types) to combinations of parameter sets (combination of farm types). Simulation results are found to be sensitive to (some) changes in parameter values but not to stochastic effects, i.e. the sequence of random numbers. The latter is shown in figure 9. The runs in figure 9 differ somewhat in quantitative terms but all show similar qualitative dynamics. The influence of random numbers is not strong enough to induce path-dependency on the macro-level as e.g. in the models of Arthur (1994). Therefore, this model is considered suitable for an approach of exploring influence of assumptions (parameter values) on model dynamics running few simulations per parameter set only and focussing on averaged results. This is important since due to limitations of time and computer resources no vast sensitivity analysis was performed and no complete exploration of the parameter space could be done.

In the stepwise approach outlined, parameter sets of later steps were partly specified based on previously gained understanding. Hence, calibration and validation are not clearly separated; especially no validation using independent data-sets could be done. Simulation results are compared to known empirical patterns manually and qualitatively, discussing findings in relation to empirical knowledge and in the context of changing boundary conditions (policies). This leaves room for subjectivity. A further more general issue regarding the modelling of complex systems is that many structurally different models may be able to reproduce specific behaviour of a complex system (e.g. Sterman 2000; Beven 2002). For these reasons, it can not be claimed that this model's structure is necessarily valid in the sense of truly resembling the structure of the real system. Consequently, the following discussion of the results obtained in the experiments described above has to be considered as thought provoking input into a debate and not as presenting unquestionable evidence.

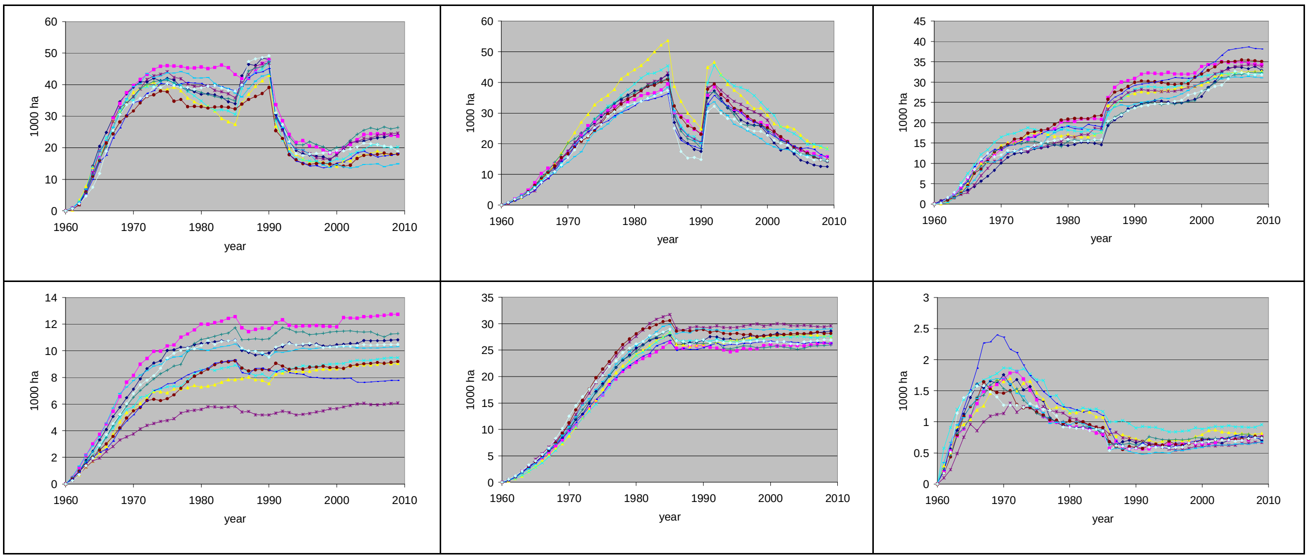

Figure 9: Ten runs with identical parameters as in table 7 but differing random number sequences. The figures show irrigated crops (from left to right and top to down): traditional cereals, high yield cereals, vineyards, melons, garlic and paprika.

7.2 Interpretation of results

A very simplistic implementation of merely profit oriented farmers turns out to be very much detached from empirical observations: all farmers, independent of the size of their farm, start to plant the most profitable option (drip irrigated garlic resp. drip irrigated melons) on the full area of their farms. They are not affected by restrictions of legal water and subsidies for cereals are insignificant in comparison to much higher profitability of horticultural crops. The model explores the effect of additional factors influencing farmers' decisions and how they increase the match between simulations results and empirical findings. Intuitively, barriers to change like sunk costs and missing skills may seem a reasonable explanation for empirically observed sticking to vineyards and cereals despite much higher profitability of horticultural crops. Also in the literature, farmers' skills, prior investments and limited capital resources are found to explain slow changes of land uses observable in agricultural systems (cf. Balmann, Dautzenberg et al. 2006). However, our model suggests that such explanations do not hold to explain the strong sticking to cereals and vineyards over the long time-span considered here. Farmers could start planting horticultural crops on small areas when conditions are favourable, e.g. when some trees reach the end of their life-span or some machinery is fully depreciated and new investments have to be undertaken anyway. Farmers can learn how to deal with horticultural crops without taking very high risk (when starting on small areas) and increase the respective areas in accordance with increasing skills.

A drawback for planting horticultural crops could be seen in risk arising from strong price fluctuations compared to e.g. cereals whose price fluctuations are limited through the CAP. But according to this model, risk does also not provide a very good explanation. Risk can be mitigated through diversification (the model considers only three horticultural crops whereas in reality even more varieties are available). Further, price fluctuations may be higher for horticultural crops but given their overall high level of gross margin, gross margin achieved is expectantly higher for horticultural crops even in bad years compared to e.g. cereals. Finally, although not considered in the model, higher average gross margin would allow for savings that would balance good and bad years.

In this model, the factor κ, representing an upper limit to the work-load manageable on a farm, is rather influential and limitations of κ constitute a necessary (although not sufficient) condition for approximating empirical data with this model. Hence κ deserves some special attention. Technically speaking, the importance of κ can be understood from the fact that κ on the one hand constitutes a strict upper limit reducing utility to zero if labour load exceeds κ and on the other hand it targets labour effort, the crop attribute which shows the strongest relative differences[10] between crops besides gross margin. Potential explanations for the existence of such an upper labour limit differ for the different farm types. Regarding business farms this has been partly discussed in section 6.2.1. Limitations of labour load must not exist per se but a similar effect may arise from a local optimum of gross margin with respect to labour input. Another explanation could be the overall availability of (qualified) workers. However, in the UGB, historically, many people left the area to Madrid because they could not find labour which makes the latter explanation somewhat implausible. Regarding family farms, limitations of labour arise from farming being a life-style rather than an enterprise only. A recent review of the literature on farmers' values, goals and objectives (Garforth and Rehman 2005) emphasises the importance of farmers' *"intrinsic orientation to work, valuing the way of life, independence and performance of work tasks above expressive, instrumental or social dimensions of their occupation."* (Garforth and Rehman 2005, p.19). This importance of intrinsic orientation, especially independence and being ones' own boss, is found to be the most important orientation for all farmers in this study; (even more highly valued by smaller farmers than by medium sized or big ones). We suggest that many aspects which farmers value about farm life, like independence, having control and working outdoors, are strongly dependent on the size of the enterprise in terms of people employed. The more people are employed on a farm, the more desktop work has to be done and the

[10] The most labour intensive crop can be (depending on land-use size much more than) five times as labour intensive as the least intensive one while e.g. water use for irrigated crops is at maximum around twice as high for the most compared to the least water-intensive irrigated crop.

bigger the need for planning and supervision. It can thus be argued that farmers prefer low labour loads that allow them to actually be a hands-on farmer and to run the farm as a family farm instead of becoming business-oriented and to become a planner and supervisor. Part-time farmers also do not primarily aim at achieving high profits but work on the farm is restricted to what is manageable in their leisure time.

In this model, no single factor explains the observed land-use changes but the model suggests that combinations of several factors result in various "logics of production", i.e. part-time farming, family farms and business-oriented farms. The model further suggests that those types feature distinct characteristics and hence exhibit quite distinct responses to driving forces of land-use change (availability of technologies, policies). It can be concluded that it is important to derive an understanding of the different characteristics of farm types when aiming at influencing land-use changes. This model can only be a first step in that direction.

Simulation results also show some short-comings of this model. This has been explicated in section 6.2.2. To summarize one can say that this model integrates various influences on utility in a way leading to a similar preference order of options for the various farm types and sizes regarding the time before 1985. The diffusion process, influenced by barriers to change, moves along similar crop levels as observed empirically. However, the model is less able to capture the responses to fast changing policies after 1985, i.e. it does not adequately capture the effect of limitations of legal water and the possibility to join the voluntary AEP programme. One explanation might be that the factors in the model are balanced wrongly but in a way that resembles the preference structue before 1985. But from our experience of working with the model, it seems more plausible that the model assumptions are partly incorrect or incomplete. The model's modular structure facilitates exploration of different or additional assumptions in future work. It is especially suitable to study alternative assumptions on farmers' decision making. For example, the implementation presented here assumes that farmers are considering all types of changes of business each year (limited to considered options, see Box 3). This assumption could be softened by changing step 2 of the decision-making algorithm (see Box 3), assuming e.g. that farmers think about improvement of their current business (however defined, e.g. by dominant type of crop) but only consider restructuring their business less frequently or in face of specific changes of boundary conditions. Such a different implementation could entail less changes between crop types. Consequently barriers might be estimated to be lower in the calibration process which in turn might effect responses to fast changing policies (cf. the differences between figure 8a and 8b). However, it is hardly possible to anticipate effects of such changes in model implementation but this has to be explored in future work. Other explanations for this model's shortcomings may be rooted in the overall design. This model focuses on the farm level and as such does not elaborate on the embedding of farms in the region through distribution channels, long-term contracts, the role of local markets, organization of local labour markets etc. Further, heterogeneity regarding soil types and groundwater availability are not considered, doing so probably overestimates the share of land that is useable to plant profitable crops.

8 Conclusions

This article presented an agent-based model developed as a thinking tool to enhance understanding of the role of farmers' characteristics for land-use change. It was applied to the case of the Mancha Occidental aquifer in the Upper Guadiana Basin, Spain. The main findings are that considering profit orientation and single additional factors (e.g. risk aversion or barriers to change arising from sunk costs and a lack of capital) seems insufficient to explain the empirically observed land-use changes. The interactions of these and further factors - including farmers' skills and respective learning processes and especially an upper limit to the work load manageable on a farm - have necessarily to be considered to reproduce inhibition of more substantial change than observed empirically. Further, different types of farms exist in the UGB (part-time farms, family farms and business oriented farms) which can be expected to differ regarding (combination of) these factors. It was shown that they can be expected to exhibit distinct responses to changes in context conditions like availability of new technologies and changing policies. It is hence important to acknowledge differences between farmers and to derive an understanding of the different characteristics of farm types when aiming at influencing land-use changes.

Although the specific findings are open to debate (see section 7.1) it can be concluded that incorporating an elaborated representation of human behaviour is crucial for understanding land-use change and that a sound understanding of the social system making use of a resource is required to solve problems of resource over-use. Key uncertainties lie in human behaviour.

Regarding the methodology applied it can be concluded that developing an agent-based model of intermediate complexity proved to be an approach which is on the one hand complex and flexible enough to incorporate quantitative as well as qualitative knowledge from various sources. This model incorporates general findings from the literature on farmer behaviour and the diffusion of innovations. Those were adapted and complemented using case specific knowledge (for example the distribution of farm sizes and the selection of factors considered based on case-specific knowledge). On the other hand, the chosen level of complexity was low enough to maintain transparency, i.e. simulation results could be traced back to underlying assumptions. Given the uncertainties regarding the structure of this model and regarding data, this is considered important because it allows developing general lines of argument which can flow into a debate. In sum, this agent-based model was found to be suitable to study influences and potential interactions of various farmers' characteristics regarding land-use change.

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Appendix

A.1 Crop attributes

Categories	**Price (1997) (€/100kg)**	**Yield rainfed (100kg/ha)**	**Yield irrigated (100kg/ha)**	**Water need irrigated (m^3/ha)**	**Variable costs rainfed (€/ha)**	**Variable costs irrigated (€/ha)**	**Applicable irrigation technology***
Traditional cereals (wheat, barley)	14	21	42	2800	130	180	R, F, S
Sunflower	20	8	18	3000	70	260	R, F, S
High yield cereals (maize, alfalfa)	15		100	5200		750	F, S
Sugar beet	5		770	6050		1500	F, S, D
Vineyards	18	50	100	2350	200	250	R, F, D
Olives	36	17	24	2050	100	150	R, F, D
Melon	27		260	4550		1000	F, D
Paprika	40		215	5900		1800	F, D
Garlic	100		74	5130		1300	F, D
* R=rainfed, F=flood irrigation, S=sprinkler, D=drip							

(sources: Aldaya and Llamas, 2008, Confederación Hidrográfica del Guadiana, 2008; Piniés de la Cuesta, 2006; Martínez-Santos, 2007; MAPA, 2008)

Labour needs according to size of respective crop area

AWU / 100 ha	< 2 ha	2-5 ha	5-10 ha	10-20 ha	20 -30 ha	30 -50 ha	50 -100 ha	> 100 ha
Trad. Cereals, rainfed	10	7	3.5	2.5	2	1.5	1	0.7
Trad. Cereals, irrigated	12	8	4	3	2.5	2	1.5	0.9
High yield cereals, irrigated	15	10	5	4	3	2.5	2	1.2
Sunflower, rainfed	10	7	3.5	2.5	2	1.5	1	0.7
Sunflower, irrigated	12	8	4	3	2.5	2	1.5	0.9
Sugarbeet, irrigated	30	20	14	11	8	7	6	5
Melons, irrigated	50	25	17	12	10	8	7	6
Paprika, irrigated	70	35	27	21	20	20	20	20
Garlic, irrigated	45	22	15	12	11	10.5	10	9.5
Vineyards, rainfed	12	7	6	5	4	3.5	3	3
Vineyards, irrigated	17	9	8	7	5.5	5	4.5	4
Olives, rainfed	8	7	6	5	4.5	4	3.5	3
Olives, irrigated	10	9	8	7	6	5	4.5	4

Labour needs of crops are estimated based on data on utilised agricultural area of holdings of different sizes and specializations, and on labour force employed by those holdings (data for Spain from Eurostat) and on Confederación Hidrográfica del Guadiana (2008) and Varela-Ortega et al. (2006). The numbers in the table relate to the mid of the respective interval. Actual labour needs for other sizes are computed using linear interpolation between those values.

Costs for water pumping are set to 0.045 Euro/m^3 (Confederación Hidrográfica del Guadiana, 2008). Labour costs are estimated as 9000 Euro/AWU based on FADN data.

A.2 Irrigation technology and calculation of water usage

	Flood irrigation	Sprinkler	Drip
Efficiency	0.5	0.75	0.9

Efficiency refers to the share of water pumped from the ground actually reaching the plant. The amount of water extracted by a farmer w_{ex} for a land-use of size s is thus calculated from the water need of the respective crop w_c and the efficiency of the applied technology e_t as:

$w_{ex} = w_c / e_t * s$

In case of rainfed cropping, the amount of extracted water is zero.

A.3 Rules

CAP

The CAP module in the model incorporates (Piniés de la Cuesta, 2006; European Commission, 1997; Council of the European Union, 1999):

1. Changes in prices for COP products (= cereals, oil-seed, proteins), i.e. in the model prices for traditional cereals, high-yield cereals, sunflower. Prices for vegetables, olives, vines and sugar beet are either not (directly) influenced by the CAP or actual market prices are above intervention prices for the period considered (hence no direct influence of intervention mechanism).

prices (€/100kg)	up to 1985	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	2005 onw.
Traditional Cereals	21	21	21	21	21	21	21	21	18.9	16.8	14	14	14	14	14	12.9	11.9	11.9	11.9	11.9	11.9
High-yield Cereals	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	20.3	18	15	15	15	15	15	13.9	12.7	12.7	12.7	12.7	12.7
Sunflower	45	45	45	45	45	45	45	20	20	20	20	20	20	20	20	17.3	15.4	13.4	13.4	13.4	13.4

2. Compensatory payments: reduction in prices for products are compensated by area specific payments (starting in 1992), including a set-aside obligation. This is distinguished in two schemes:
   a. Simplified scheme: a farmer's COP area is less than 43.8ha (specified as 92t of yield in the regulation, corresponding area calculated from regional factor). In this scheme, there is no set-aside obligation; compensatory payments are paid for all COP areas with the compensation rate of traditional (rainfed) crops. Max set-aside area is equal to COP area excluding set-aside, (i.e. at maximum half of total area may be set-aside).
   b. General scheme: yield corresponds to more than 92t (area > 43.8 ha). Then there is a set-aside obligation in percent of COP area. The exact percentage has been defined on a yearly basis and has hence changed over years. In the model, set-aside obligation is always 10% of COP area. Maximum set-aside area is equal to COP area excluding

set-aside (i.e. at maximum half of total area may be set-aside). If these requirements are met, crop specific compensatory payments are paid (see table below).

Rule of "eligible land": only area of land which was dedicated to annual crops in 1991 compensation may be claimed for. In this model, eligible land is saved in 1991 as total farm area minus area of tree crops.

€ per ha	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Trad. Cereals rainfed	0	38	75	114	114	114	114	114	123	132	132	132	132	132
Trad Cereals irrigated	0	75	151	228	228	228	228	228	247	265	265	265	265	265
High Yield Cereals	0	109	219	331	331	331	331	331	358	384	384	384	384	384
Sunflower	198	198	198	198	198	198	198	198	172	152	132	132	132	132
Set-aside	145	145	145	145	145	145	145	145	123	132	132	132	132	132

Water Law / Pumping quotas

The 1985 water law entitles groundwater rights based on previous use. Based on this, the pumping quotas then introduce a strict reduction on the water use allowed per hectare (Llamas and Martínez-Santos, 2005; Varela-Ortega, 2007; Piniés de la Cuesta, 2006; Rosell and Viladomiu, 1997; Lopez-Gunn, 2003; Rosell and Viladomiu, 1997). The actual water quotas have been adapted on a yearly basis but are simplified in the model focussing on the main changes as described in the following.

Farmers irrigated areas are memorized in 1985 (excluding vineyards, vineyard irrigation is forbidden at that time). From 1986 onwards farmers are allowed to use a baseline quota of 4278m^3 of water per ha of entitled land which is irrigated (excluding vineyards).

From 1991 onwards pumping quotas are introduced with water rights based on the baseline quota as follows: 100% for the first (up to) 5 ha, 50% for the next (up to) 5ha, 35% for the next (up to) 20ha and 25% for the rest of the land.

From 1997 onwards vineyards may be irrigated but only a reduced amount of water is granted (the baseline quota for vineyards is 2000m^3/ha compared to 4278m^3/ha for other crops). In the model, water rights arising from a mix of areas of vineyards and other crops are computed as follows: the entitled area is "filled" with non-vine land as much as possible (to take advantage of the higher quota) and then filled up with vine area. Based on the respective shares a weighted quota is calculated and the corresponding water rights for the farm size are calculated as outlined above.

The water law imposes a fine of with 7 cents/m^3 water abstracted illegally. However, it is nearly not controlled at all. In the model there is an assumed efficiency of control of 1% (1% of violations of this law are detected and have to pay the fine). It is assumed that farmers include a rational calculation of this risk to pay a fine in their calculation of gross margin, i.e. a penalty is included in the gross margin:

$Max(0, (water_{extracted}-water_{allowed}))*0.07Euro/m^3*0.01.$

AEP

From 1993 onwards, farmers are offered direct payments in exchange for voluntarily cutting down on water use. Farmers, who choose to adhere to the programme, receive payments in proportion to water savings related to initial entitlements under the 1985 Water Law. The AEP is modified in 2003. For this second phase, allowed water use volumes and respective reductions are calculated based on the water volumes established annually under the pumping quotas (sources: Llamas and Martínez-Santos, 2005; Varela-Ortega, 2007; Piniés de la Cuesta, 2006; Rosell and Viladomiu, 1997). Note that there is a period (1993-2002) in which the AEP may grant more water than the pumping quotas do. In this case, in the model, farmers who subscribe to the AEP are considered acting legally.

In this model, the land-use pattern of farmers is memorized in 1992. The potential AEP area is calculated as area of all crops excluding vineyards. This area is adapted: in 1998-2002 olives and vineyards are excluded, since 2003 nothing is excluded. The maximum water quotas are calculated based on this area for each farmer, according to the chosen level of reduction (50%, 70% or 100%) with respect to a baseline amount of water which is 4278m^3 per ha for 1993-2002 and the respective pumping quota (including size specific reduction) from 2003 onwards. The 70% option is no longer available after 2003.

Compensatory payments then are for the options and years (Varela-Ortega, 2007):

Compensatory payments (€/ha)	1993 …	1997 …	2001 …	2003…2006
50%	156	164	179	1-40ha→209 40-80ha→125 >80ha→63
70%	258	271	296	(no longer available)
100%	360	379	414	1-40ha→518 40-80ha→311 >80ha → 155

The modulation since 2003 means that each farmer gets the highest compensation for the first 40ha, for next 40 ha (40-80 ha) less etc.

Each year for each considered land-use pattern each option is checked (including non-participation). The option with highest payment is chosen (i.e. farmers participate in AEP if their land-use pattern allows to get AEP payments).

Vine irrigation banishment

Before 1997 irrigation of vineyards was forbidden (Lopez-Gunn, 2003). This rule renders all land-use patterns illegal which include irrigated vineyards (only applicable before 1997).

A.4 Calculation of risk associated with a land-use pattern

"Risk" refers to variability of gross margin due to short-term fluctuations of prices for products and inputs as well as variability of yields (due to weather conditions, pests etc.). More long-term uncertainty associated with changing policies, effects of innovations adopted and general economic trends are not included (but represented in the distance d_c capturing investment decisions).

The risk function is designed to capture the following characteristics of risk: a) some crops are inherently more risky than others, b) diversification reduces risk, c) irrigation reduces risk, d) subsidies paid per crop area reduce risk since they are independent from variability in prices and yields.

The risk r associated with a land-use pattern p_i consisting of land-uses l_j with crops l_j^c and technology category l_j^t (=rainfed or irrigated) and sizes $s(l_j)$ is calculated as follows:

$r(p_i) = Min(\frac{V_{inc}(p_i)}{g_{\exp}(p_i)}, 1.0)$	Maximum risk is 1.0 and is reached when the variation in income equals the expected gross margin: $V_{inc}(p_i) \sim g_{exp}(p_i)$. Assuming a normal distribution of income with standard deviation V_{inc}, this means that in ~30% of the years the actual gross margin is only 50% or less of the expected gross margin which is assumed to be unbearable for farmers.
$g_{\exp}(p_i) = \sum_{l_j} yield(l_j) \cdot price(l_j^{\,c}) + subsidies - \cos ts$	g_{exp} is the expected gross margin (income – costs). Yield independent subsidies reduce risk while costs (variable costs, labour, water) increase risk.
$V_{inc}(p_i) = \sqrt{\sum_k V_{c_k}(p_i)^2}$	$V_{inc}(p_i)$ is the variation in income. It decreases with diversification (and thus risk decreases). The marginal effect on risk reduction diminishes for increasing diversification.
$V_{c_k}(p_i) = \sum_{l_j} stdev(l_j^{\,c}, l_j^{\,t}) \cdot s(l_j)$ $with \quad l_j^{\,c} = c_k$	The stdev of all areas dedicated to the same crop are aggregated, so diversification across different irrigation technologies does not reduce risk.

stdev(c,t) is specific for each crop and technology class and estimated based on empirical data on yields and prices for Spain in the period 1985-2005[11] (Eurostat, INE). In order to extract yearly fluctuations, long-term trends in the data were removed (a linear regression was made and the trend removed from the data). Standard deviations were calculated for yields, prices and *yields*prices* to

[11] Exceptions: for sunflowers data from 1992 onwards was used due to a very strong drop in prices from 1991 to 1992 which results in artificially high variance (see CAP prices above); for garlic and paprika prices were only available from 1990 onwards; for olives yields were only available until 2003 and for grapes only until 2002. Data on prices for grapes was not available.

identify sources of variability. Correlations between yields and prices were also considered. Based on this assessment relative standard deviations $stdev_{rel}(c,t)$ of income generated on one ha of land were defined. $stdev(c,t)$ is then calculated during simulation runs as $stdev_{rel}(c,t)*price*yield$ to incorporate changes in prices for COP products due to policy changes. The value taken for $stdev_{rel}(c,t)$ in the model is not always exactly the value found empirically because for example for traditional cereals (wheat, barley) standard deviation is empirically much bigger than for maize. However, most area of traditional cereals entering the statistic is rainfed and most maize area is irrigated. The difference likely can be explained through this. Hence for irrigated traditional cereals the relative standard deviation of income generated on one ha of land is assumed to be similar to that of maize. For grapes (vineyards) no data on prices was available but only on yields. Here, standard deviations had to be estimated based on yields and based on ranges of variability found for other crops.The following table shows resulting risk considering costs (except costs for labour) but not including subsidies. Note that subsidies and labour costs can make a difference.

Crop type	yield * price (€/ha)*	stdev (€/ha)	costs (€/ha)+	risk (per ha)
Rainfed crops				
Traditional cereals	441	75	130	0.24
Sunflower	360	79	70	0.27
Vine	900	225	200	0.32
Olives	612	165	200	0.32
Irrigated crops				
Traditional cereals	882	53	306	0.19
High yield cereals	2250	135	984	0.11
Sunflower	810	122	395	0.29
Sugar beet	3850	347	1772	0.17
Vine	1800	234	356	0.16
Olives	864	216	342	0.35
Melons	7020	1053	1205	0.18
Paprika	8600	1118	2066	0.17
Garlic	7400	814	1531	0.14

* *1990 prices*

+ Regarding costs for water assuming irrigation efficiency is 100%. Costs for labour are not considered since they are dependent on the size of a land-use.

A.5 Calculation of distances between land-use patterns

Two different distances $d_s(f, p_i)$ and $d_c(p_0, p_i)$ between a farmer f respectively his current land use pattern p_0 and a potential future land-use pattern p_i are calculated:

a) $d_s(f, p_i)$ is a distance reflecting learning efforts and uncertainty related to the skills of a farmer
b) $d_c(p_0, p_i)$ is a distance representing investments and capital losses arising from changes in a farmer's land-use pattern.

<u>$d_s(f, p_i)$: learning efforts and uncertainty related to skills</u>

Farmers have skill values s_{ci} (s_{ti}) in [0,1] for all crops (technologies). Skills increase in each year a crop or technology is part of a farmer's land-use pattern. The process is modelled as asymptotic process (explicated here for crops only but similarly computed for technologies):

$$s_{c_i}(t+1) = s_{c_i}(t) + (1 - s_{c_i}(t)) / m$$

m is a constant determining the speed of the learning process. In the simulations presented it is set *m=3*, i.e. a farmer's skill is *1/3* after one year of experience with a crop or technology and after 5 years it is *~0.87*.

Learning efforts and uncertainty involved in a changing land-use pattern are computed from farmers' skills and - to model the change to new crops and technology - further from matrices describing the distances between different crop classes ($d_s^c(c_1,c_2)$) and technologies ($d_s^t(t_1, t_2)$):

$d_s^c(c_1, c_2)$	COP	OFC	Horticulture	Tree crop
COP	0.05	0.3	1.0	1.0
OFC	0.3	0.2	1.0	1.0
Horticulture	0.5	0.5	0.5	1.0
Tree crop	0.5	0.5	1.0	1.0

Distances of crop class c_1 (line) to c_2 (column): distances within one class refer to changes from one crop in that class to another one, e.g. changing from barley to maize (both COP) gives 0.05 while changing from paprika to garlic (both horticulture) is assumed to be more complex: 0.5. Some crops are considered in general to be easier to farm (COP, OFC), than others (horticulture, tree crops), what is reflected in lower values in those columns.

$d_s^t(t_1, t_2)$	Rainfed	Flood	Sprinkler	Drip
Rainfed	0.0	0.5	0.8	1.0
Flood	0.0	0.0	0.3	0.5
Sprinkler	0.0	0.0	0.0	0.3
Drip	0.0	0.0	0.2	0.0

All farmers know about rainfed cropping. There is no uncertainty or learning involved. Doing irrigation with flooding is comparably easy and does not involve much technical equipment, however, a farmer must learn when and how much to irrigate. Sprinkler and drip involve more complex technology, whereas drip is considered to be more complex than sprinkler. Experience with sprinkler resp. drip irrigation requires some technical understanding, easing the adoption of the respectively other technology compared to a farmer only knowing flood irrigation.

$d_s(f, p_i)$ is defined as the sum of lack of experience regarding all crops (technologies) in a potential future land-use p_i, weighted by the respective $area(c_i)$ of new or extended crops (technologies). A lack of experience of *f* regarding new crops (technologies) in p_i is computed as minimum distance to any crop (technology) *f* has used previously during the simulation, considering *f's* experience. A factor w_{tech} regulates the importance of uncertainty and learning related to irrigation technology. In the simulations presented w_{tech} is set to *0.5*, assuming a stronger influence of crops compared to irrigation technology. The result is divided by the *size* of the farm. Thus:

$$d_s(f,p_i) = [\sum_{c_1 \in p_i} l_c(f,c_1) \cdot area(c_1) +$$
$$w_{tech} \cdot \sum_{t_1 \in p_i} l_t(f,t_1) \cdot area(t_1)] / size$$

with

$$l_c(f,c_1) = \begin{cases} \min_{c_2, s_{c_2} \neq 0} [d_s^{\,c}(c_1,c_2) \cdot (1+(1-s_{c_2}))], & if\ s_{c_1} = 0 \\ (1-s_{c_1}) & , \ else \end{cases}$$

Note that $d_s(f, p_i) > 1.0$ may be, e.g. if the total area of the farm is within one year shifted from rainfed cereals to drip irrigated vineyards. Regarding the random influence of $d_s(f, p_i)$ as described in Box 4, such changes have probability zero to be implemented.

$d_c(p_0, p_i)$: capital reallocation: investments and sunk costs

$d_c(p_0, p_i)$ is calculated based on distances of crops (and technologies) regarding the use of similar assets. In this simplified representation, investments and sunk costs are not differentiated according to their contribution to "distance" but integrated in an overall rough estimation of distances between land-uses.

Related to crops: The distances between crop classes are defined in $d_c^{\,c}(c_1, c_2)$:

$d_c^{\,c}(c_1,c_2)$	COP	OFC	Horticulture	Tree crop
COP	0.1	0.2	0.5	0.8
OFC	0.2	0.1	0.5	0.8
Horticulture	0.5	0.5	0.2	0.7
Tree crop	0.8	0.8	0.7	1.0

For changes within the COP class most assets can be re-used. Also changes from COP to OFC and within OFC, much can be re-used (tractor, plug,…). Horticulture involves more hand-labour and less expensive machinery, therefore capital losses are low for changing from horticulture to some other land use and investments are low for changes to horticulture; however, investments are necessary to change from horticulture to COP, OFC or tree crops. A change from tree crops to other crops involves loss of trees, therefore capital loss is high. Investment in tree crops is also considered high since trees do not produce yield (or little yield) in the first years and thus those times have to be bridged using savings or other income.

A matrix $R(p_0,p_i)$ is computed which describes the re-allocation of crop type areas. *R* is computed using a heuristic algorithm based on the structure of the matrix $d_c^{\,c}(c_1, c_2)$ and does not include areas that remain unchanged from p_0 to p_i. The distance between land-use patterns related to crops is then computed by summing up the products of the respective matrix entries and normalized using the *size* of the farm:

$$d_c^{\,c}(p_0, p_i) = \sum_{i,j} d_c^{\,c}(c_1,c_2)_{i,j} \cdot R(p_0,p_i)_{i,j} / size$$

Related to irrigation technologies: unused capital comprises sprinkler or drip irrigation equipment which is not used in p_i as well as water pumping capacity which is not fully exploited. Investments on the other hand comprise new sprinkler or drip assets as well as newly drilled wells. The area irrigable with sprinkler ($a_s(x)$) resp. drip ($a_d(x)$) of p_0 and p_i is compared, normalized by relating it to the total *size* of the farm and weighted (w_s and w_d, both set to 0.5). The extracted amount of water ($e(x)$) for p_0 and p_i is compared and normalized by the maximum extraction e_{max} (=using the most water intensive option on the whole farm) and weighted (w_w = 0.5). In total $d_c^t(p_0, p_i)$ ranges in [0,1] (note that some area is dedicated to one irrigation technology only):

$$d_c^{\,t}(p_0, p_i) = |a_s(p_i) - a_s(p_0)| / size \cdot w_s + \\ |a_d(p_i) - a_d(p_0)| / size \cdot w_d + |e(p_i) - e(p_0)| / e_{\max} \cdot w_w$$

The two parts $d_c^c(p_0, p_i)$ and $d_c^t(p_0, p_i)$ are added to the total distance related to capital. w_{tech} is set again to *0.5* :

$$d_c(p_0, p_i) = d_c^{\,c}(p_0, p_i) + w_{tech} \cdot d_c^{\,t}(p_0, p_i)$$

A situation specific factor modulates d_c (p_0, p_i). The rationale behind is that to reduce model complexity, the model does not keep track of all different kinds of investments made by farmers (this would imply knowing life-times of many assets, implement decisions on purchase etc.), neither are external conditions like interest rates simulated explicitly. Therefore, $d_c(p_0,p_i)$ can not be explicitly specific to the age of assets and external circumstances. However, in reality the age of assets will make a difference, especially that of tree crops. To represent heterogeneity in barriers to change arising from the specific situation on a farm, a random factor is included. It is assumed that the status of the various kinds of assets adds up to a certain factor *r* which is then multiplied to $d_c(p_0,p_i)$. This can further be interpreted as also capturing variable external conditions like prices for used assets, interest rates etc. as well. The integration of various (independent) "random" aspects in this factor *r* entails higher probabilities for factors "averaging out" than for adding up to extreme values. Therefore *r* is modelled as normally distributed number (mean = 1.0, sd=0.167, bounded by {0,2}).

A.6 Model initialization

The model starts before irrigated crops were introduced in the study area. The initial model state thus comprises only rainfed crops, namely traditional cereals, vineyards, olives and fallow land.

The initial areas of crops in the study area are estimated based on empirical data as follows. As a basis, data for the "comarca La Mancha" (in Ciudad Real) for 2001 is used (CHG 2006). The comarca La Mancha can be used as approximation for the Mancha Occidental Aquifer (Pedro Zorilla, personal

communication). Data for the autonomous Region Castilla La Mancha (Eurostat), available since 1990, was used to estimate trends for the period 1990-2001. Data for Spain (Eurostat), available since 1965, was used to estimate trends for the period 1960-1990. It was assumed that horticulture coming up in later years was planted partly on smaller farms which initially likely had vines and partly on previous cereal area and that sugarbeet was planted on previous cereal area.
This leads to estimated areas of crops in 1960 (in % of total area of the MOA): cereals 20%, vineyards 45%, olives 10%, fallow 25%.

We defined four farmer types:

- SV: specialist vineyards (80% vineyards, 20% fallow)
- SO: specialist olives (80% olives, 20% fallow)
- SC: specialist cereals (70% cereals, 30% fallow)
- M: mixed (20% vineyards, 10% olives, 40% cereals, 30% fallow).

Those were related to the different farm sizes based on general tendencies (smaller farmers have rather vineyards and olives, bigger ones rather cereals) reflected in data from Eurostat and in sources such as (Llamas and Martínez-Santos, 2005):

	SV	SO	SC	M
Very small	60%	40%	0%	0%
Small	60%	20%	0%	20%
Medium 1	80%	0%	0%	20%
Medium 2	50%	0%	30%	20%
Big	0%	0%	80%	20%

This results in the following initial crop areas (empirically estimated areas in brackets): cereals 22.04% (20%), vineyards 45.01% (45%), olives 9.05% (10%), fallow 23.89% (25%), matching approximately the empirically estimated areas.

Percentage of farm types proposed in table 4 were derived as follows*:*
Part-time farms:

- "Owner works mostly off-farm" in 28.5% of cases in Spain (Eurostat).
- "Work time of holder" is 0-25% in 51,7% of cases (in Spain) respectively 67,3% (in Ciudad Real) (Eurostat).
- Assuming that share of "owner works mostly off-farm" in the UGB relates to the number for Spain similarly as "work time of holder" it follows part-time farmers are 28.5%*67.3%/51.7% = 37.1% of all farmers.

Business-oriented farms:

- We use the differentiation between family and non-family farms suggested by Hill (1993) (FWU>0.5AWU, i.e. including here Hill's "intermediate farms" in family farms). Hill identifies for Spain (1989) 16.5% of farms which are non-family. However the FADN data used covers only 48.9% of Spanish farms, excluding small ones which are likely not business-oriented farms. A first estimate of non-family farms (i.e. our business-oriented farms) would thus be 16.5%*48.9%= 8.1%.

- The average AWU/holding in Ciudad Real is only 65.7% of Spanish average and there are considerably more farms with "work time of holder <50%" in Ciudad Real than in Spain (factor = 1,18; these are likely mostly part-time farmers but could also be business farmers who do not work the land themselves). On the contrary, the share of holdings with ≥50ha (likely being business farms) is higher in Ciudad Real than in Spanish average. I.e. evidence on differences between Ciudad Real and Spanish average remains inconclusive.

Family farms: we take the difference between total farms and part-time + business oriented.

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