Decision-Making in Public Good Dilemmas: Theory and Agent-Based Simulation

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Zusammenfassung

In vielen Zusammenhängen finden sich Menschen in Situationen wieder, in denen sie die Wahl haben zwischen Verhaltensweisen, die einem kollektiven Zweck dienen oder solchen, die die persönlichen Interessen befriedigen und das Kollektiv ignorieren. In manchen Fällen wird das unterliegende soziale Dilemma (Dawes, 1980) gelöst und kollektive Aktion (Olson, 1965) gezeigt. In anderen Fällen bleibt die soziale Mobilisierung erfolglos. Der zentrale Inhalt der Forschung zu sozialen Dilemmata ist die Identifikation und das Verständnis der Mechanismen, die die beobachtete Kooperation erzeugen und damit das soziale Dilemma auflösen. Das Ziel dieser Arbeit ist es, zu diesem Problembereich für die Unterklasse der Gemeingutdilemmata beizutragen. Um dieses Ziel zu erreichen, werden die wichtigsten Befunde aus existierenden Vorarbeiten rekapituliert und Anforderungen an die Theorie- und Methodenbeiträge dieser Arbeit abgeleitet.

Insbesondere nimmt die Arbeit die dynamischen Mobilisierungsprozesse in den Blick, die kollektive Aktion fördern oder hemmen. Grundlage ist die Einsicht, dass der Erfolg oder Misserfolg der erforderlichen sozialen Mobilisierung zentral determiniert ist durch im Allgemeinen heterogene individuelle Präferenzen der Mitglieder der bereitstellenden Gruppe, die soziale Struktur, in die die handelnden Individuen eingebunden sind und die Einbettung der Individuen in einen ökonomischen, politischen oder biophysikalischen Kontext.

Um diesen Aspekten und den involvierten Dynamiken Rechnung zu tragen, ist die Methode der Wahl ist die agentenbasierte Simulation sozialer Systeme. In besonderer Weise zielführend sind solche Agentenmodelle, die für Simulation von menschlichem Verhalten auf geeignete psychologische Handlungstheorie zurückgreifen. Diese Arbeit entwickelt die Handlungstheorie HAPPenInGS (**H**eterogeneous **A**gents **P**roviding **P**ubl**i**c **G**ood**s**) und zeigt deren Einbettung in verschiedene Multiagentensimulationen. Der besondere Mehrwert dieses methodischen Zugangs wird in der Arbeit demonstriert: Ausgehend von einer Theorie des *individuellen* Handelns werden in den Simulationen *kollektive* Verhaltensweisen in ihrer Genese beobachtet, analysiert und in Szenarienanalysen bewertet. Diese Klasse von Resultaten liefert Einblicke, die dem klassischen empirischen Zugang verschlossen bleiben und aus denen politikrelevante Empfehlungen motiviert werden können.

Summary

In many real world contexts individuals find themselves in situations where they have to decide between options of behaviour that serve a collective purpose or behaviours which satisfy one's private interests, ignoring the collective. In some cases the underlying social dilemma (Dawes, 1980) is solved and we observe collective action (Olson, 1965). In others social mobilisation is unsuccessful. The central topic of social dilemma research is the identification and understanding of mechanisms which yield to the observed cooperation and therefore resolve the social dilemma. It is the purpose of this thesis to contribute this research field for the case of public good dilemmas. To do so, existing work that is relevant to this problem domain is reviewed and a set of mandatory requirements is derived which guide theory and method development of the thesis.

In particular, the thesis focusses on dynamic processes of social mobilisation which can foster or inhibit collective action. The basic understanding is that success or failure of the required process of social mobilisation is determined by heterogeneous individual preferences of the members of a providing group, the social structure in which the acting individuals are contained, and the embedding of the individuals in economic, political, biophysical, or other external contexts.

To account for these aspects and for the involved dynamics the methodical approach of the thesis is computer simulation, in particular agent-based modelling and simulation of social systems. Particularly conductive are agent models which ground the simulation of human behaviour in suitable psychological theories of action. The thesis develops the action theory HAPPenInGS (**H**eterogeneous **A**gents **P**roviding **P**ubl**i**c **G**ood**s**) and demonstrates its embedding into different agent-based simulations. The thesis substantiates the particular added value of the methodical approach: Starting out from a theory of *individual* behaviour, in simulations the emergence of *collective* patterns of behaviour becomes observable. In addition, the underlying collective dynamics may be scrutinised and assessed by scenario analysis. The results of such experiments reveal insights on processes of social mobilisation which go beyond classical empirical approaches and yield policy recommendations on promising intervention measures in particular.

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1 Introduction

1.1 Motivation and objectives

Imagine a community of small-scale farmers who face the risk of losing their crop because of unpredictably occurring high water events. A system of canals capable of draining away excess water to a nearby river could help eliminating or mitigating such negative effects. However, run-off water has to be drained through a sequence of channel segments to reach the river and each segment is located on the field of a different riparian land owner. Therefore, for a farmer, facilitating drainage on his[1] field is only beneficial if other farmers join in and do the same on their fields. Should he wait and hope that neighbours provide enough drainage capacity to protect his field as well? Or is it a good thing to be the first to start a collective effort?

Now imagine an urban neighbourhood where some of the residents, e.g. solitary-living elderly, depend on frequent medical assistance and help. Commonly, public health service would provide the required care-taking activities for such persons at risk. However, under some more or less unpredictable circumstances these services might temporarily fail. Under such conditions self-organised neighbourhood help could supplement public health care. To be effective, neighbourhood help has to be supported by a sufficient number of neighbourhood members. Still, from the perspective of an individual resident, the question remains whether he should devote part of his spare time to neighbourhood support, or simply remain passive, expecting his neighbours to contribute.

Whereas the two outlined situations stem from entirely different contexts, they share common features when focussing on the decision situation of an individual, i.e. a farmer or a neighbourhood resident. Both situations are characterised by the fact that an individual's interests are at odds with the collective interests of his group. In both cases, all members of a group (farmer community, residential neighbourhood) benefit from a collectively generated commodity (drainage system, neighbourhood help) while the individual is free to

[1] Throughout this thesis the pronouns "he" or "his" stand interchangeably for the formulations "he or she" and "his or her" respectively.

choose whether he contributes to the provision of the good, or whether he simply enjoys the publicly accessible benefits and remains passive.

It is the purpose of this thesis to describe and investigate the provision of a public good in a temporally and spatially dynamic model. The basic understanding is that success or failure of the required process of social mobilisation is determined by

(1) heterogeneous individual preferences of the members of a providing group,
(2) the social structure in which the acting individuals are contained, and
(3) the embedding of the individuals in economic, political, biophysical, or other external contexts.

To account for these aspects and for the involved dynamics the methodical approach of the thesis is computer simulation, in particular agent-based modelling and simulation. The thesis will demonstrate how agent-based models which are thoroughly grounded in existing theoretical and empirical work from multiple disciplines can help to investigate and understand the interplay of factors (1), (2), and (3) in real world case study contexts.

1.2 Structure of the thesis

Be it the farmers or be it the neighbourhood residents – their respective decision situation may usefully be conceptualised as a social dilemma, in particular a public good dilemma. Chapter 2 reviews existing work that is relevant to this problem domain. The review covers quite diverse scientific disciplines and pulls together the insights offered by each perspective in five specific synthesis sections. The rationale is to carry forward the conclusions into the following chapter in order to guide theory and method development. As a first contribution, chapter 2 substantiates the theoretical embeddedness into the domain of social dilemmas. On the one hand this conceptualisation provides a succinct definitional specification of the problem class. On the other hand it links the problem domain to a rich body of existing empirical work. The second contribution of chapter 2 is the introduction of the main methodical approach of the thesis which is agent-based modelling and simulation of social systems (ABSS). Finally, chapter 2 completes the picture by giving a focused introduction to the concepts relevant to psychologically sound ABSS.

Chapter 3 reports on the main theoretical and methodical contributions of the thesis. Based on the insights obtained in chapter 2 we propose a theory of individual decision-making in public good dilemmas, namely the HAPPenInGS model (**H**eterogeneous **A**gents **P**roviding **P**ubl**i**c **G**ood**s**). Furthermore, the embedding of the theory in an ABSS is demonstrated. It is shown that the dynamical analysis of the abstract ABSS enables theory validation on one hand and guides case-specific model parameterisation on the other.

Chapter 4 applies HAPPenInGS in the real world case study context of neighbourhood support in Northern Hesse under conditions of climate change. From a methodical point of view it is demonstrated how HAPPenInGS is instantiated for a specific case by linking it to real world empirical data. Among other results, simulations with the case study model allow to observe how intervention campaigns help to break prevailing habits in a population and establish new behavioural patterns that persist after the end of the intervention.

The second real-world application of HAPPenInGS is the case of land reclamation in the Polish Odra valley for which modelling and simulation results are presented in chapter 5. Despite the common theoretical grounding in HAPPenInGS, the Odra case ABSS investigates different dimensions of social mobilisation compared to the case of neighbourhood support. The unique empirical features of the Odra case allow e.g. discussing the influence of structural asymmetries of the social dilemma on social mobilisation and investigating the impact of financial incentives on collective action by means of simulation experiments.

Chapter 6 summarises the main results of the thesis, compares and discusses the insights from the case specific simulation exercises, and proposes future work.

2 Theoretical background, related work and implications

This chapter reviews and discusses work that is relevant to the problem domain of decision-making in public good dilemmas. The rationale is to provide a comprehensive set of different scientific perspectives on the problem domain, and to pull together the insights offered by each perspective in terms of mandatory requirements of the research method to be developed. These requirements cover implications from existing work as well as gaps identified and serve as a set of benchmark criteria for method development.

Section 2.1 provides the classical game-theoretic conception of social dilemmas and its relation to existing real-world evidence provided by different empirical approaches. The section concludes by giving an integrated systems view on the problem domain and by deriving a first set of four requirements.

The following section 2.2 introduces the method of agent-based modelling and simulation of social systems (ABSS). The section's main statement is that ABSS is a method that can in principal account for the requirements derived in the previous section. Subsequently, we narrow the ABSS focus to existing modelling exercises in the domain of social dilemmas and conclude by formulating two additional requirements specific to ABSS.

Section 2.3 adds on the perspective of general psychological decision theory and identifies the Theory of Planned Behaviour as a suitable social-psychological theory framework.

Section 2.4 concludes by summarising the main insights obtained.

2.1 *Social dilemmas and public goods*

This section gives an overview of the classical theoretical and empirical approaches of social dilemma research.

In section 2.1.1 we introduce the relevant building blocks from literature following the typical sequence used in the respective seminal papers: Sections 2.1.1.1 to 2.1.1.3 are devoted to the classical game-theoretic embedding of social dilemmas that use the prisoner's dilemma metaphor. Section 2.1.1.4 presents the classical definition of a social dilemma (Dawes, 1980). Following Dawes' arguments this definition acts as an interface between game-theory and psychology. Section 2.1.1.5 briefly highlights some general empirical observations and introduces the two main families of social dilemmas namely public good dilemmas and resource dilemmas.

The goal of section 2.1.2 is to provide a sufficiently complete overview of the individual and situational factors that scholars found to have influence on the rate of cooperation in social dilemmas. These factors provide reasonable dimensions for describing the possible facets of social dilemmas. Our argument is that the requirements for the research method should be guided by these dimensions.

Section 2.1.4 extracts the key insights from the previous sections. Two main contributions are made: Firstly, we give an integrated systems perspective on public good dilemmas. This notion explicitly reflects the understanding that individuals are embedded in different environmental contexts and that social dilemmas may arise from their interaction with these environments. From this conception follows the second contribution of the section that is the initial set of requirements for the research method to be developed.

2.1.1 Game-theoretic background and empirical evidence

2.1.1.1 Game theory

The most common theoretical framework of social dilemmas is mathematical game theory, which belongs to the field of rational choice theory (Gibbons, 1997; Nash, 1951; von Neumann & Morgenstern, 1947). Game theory studies mathematical models of conflict and cooperation between intelligent rational decision makers (mostly called players). Two different classes of games are usually distinguished: We talk about a zero-sum game if the gain of one player is always balanced by equal losses of one or more of the other players. If gains and losses are not necessarily balanced the game is called a non-zero-sum game. Game theory formalises a strategy of a decision maker as a rule allowing the player to choose his next action in any given situation. The success of a player's strategy is determined by the interaction with other players, i.e. the interaction of the respective strategies.

The core postulation of game theory is that individuals are rational actors striving to maximize their utilities. These assumptions yield some strong implications e.g. on the existence of an equilibrium state of the players' interaction, i.e. a situation when the players' behaviours converge to some stable state and do not change subsequently. The Nash equilibrium (Nash, 1951) describes a situation in which no player can benefit from changing his strategy assuming that all other players keep their respective strategy choices unchanged. In general, for a given game there may be more than one Nash equilibrium. In addition, equilibriums may differ in the respective payoff achieved by the players.

In game theory, utility is often narrowly defined in terms of people's material self-interest and disregards other dimensions. The notion of equilibriums and especially the Nash Equilibrium is built on the assumption that each player has a fixed set of behavioural options and complete knowledge of the associated utilities as well as full knowledge of the strategies used by all other players. Furthermore, it is assumed that a player processes this information in total in order to optimise his strategy.

This rational actor postulation was largely adopted in various disciplines, e.g. in neoclassical economics. However, the assumptions on a rational decision-maker's computational capabilities required in order to optimise strategies with respect to utilities are fundamentally implausible from cognitive science point of view. Economist and cognitive scientist Herbert Simon reacted by proposing a notion of bounded rationality and satisficing as an alternative to full, unbounded rationality and optimising (Simon, 1955). This conception is well accepted in psychological research and was e.g. further refined by introducing the concept of "fast and frugal" decision heuristics (Gigerenzer, Todd, & Abc Research Group, 1999) that carry forward the notions of satisficing and bounded rationality into psychological decision theory.

2.1.1.2 The prisoner's dilemma

Research on social dilemmas goes back to the classical prisoner's dilemma (PD; Tucker, 1950; Luce & Raiffa, 1957) which originates from the field of game theory. In terms of game theory the PD is a non-zero-sum game with two players where each player decides between a cooperative, social-oriented behaviour and a defective, egoistic behaviour. Incentives are set such that individually rational decisions lead to collectively inferior results. The problem is called the prisoner's dilemma, because it is an abstraction of the situation felt by a prisoner who can either cut a deal with the prosecutor and tell on his partner (defect) or keep silent and therefore tell nothing of the crime (cooperate). The core structure of a PD is usually brought down in terms of matrix that relates individual decisions to an abstract payoff. The payoff matrix for the PD is displayed in the table below.

		Player A	
		C	D
Player B	C	R, R	S, T
	D	T, S	P, P

Table 1. Payoff matrix of PD. Players decide to either defect (D) or to cooperate (C). For each of the four possible combinations of player decisions the matrix displays the payoffs that go to player A and player B respectively.

The two players have a choice to cooperate, C, or to defect, D. If both cooperate they receive a payoff R. If both defect, they receive a lower payoff P. A defector versus a cooperator gains the highest payoff, T, while the cooperator is left with the lowest payoff S. The game is a PD if $T>R>P>S$. Therefore, in terms of the sum of payoffs mutual cooperation is superior to mutual defection because $R>P$. However, in a non-repeated PD, it is (rationally) best to defect, because $T>R$ and $P>S$ and the only concern of each individual player is to maximize his payoff during the one interaction.

Clearly, the PD pins down the core characteristics of a multitude of decision situations that are determined by a conflict of individual and collective rationality. The classic PD has been applied as a powerful metaphor to numerous real world problems like the nuclear arms race

(Hardin, 1983), climate change (Soroos, 1994) and many others. However, in being a robust and abstract description the PD misses out some important characteristics of real-world individual interaction. Firstly, the PD assumes two isolated decision-makers deciding on only one topic. Real decision situations mostly include groups of communicating decision-makers interacting in various different decision contexts. Additionally, the simple PD does not include players' memories of past interactions or strategies (see section 2.1.1.3). Finally, the underlying postulate of rational decision-makers is highly questionable as discussed in the previous section.

2.1.1.3 The iterated prisoner's dilemma

In essence, the one-shot PD sets the players as naturally selfish individuals. Cooperation becomes an option if the game is repeated as the selfish player recognises that he cannot make a good choice without knowing what the other one will do. The iterated PD (IPD, Axelrod, 1984) is a PD that is repeated for a finite number of times with the same two players. In order to preserve structural characteristics of the PD, in the IPD it is usually assumed that $R > (T+S)/2$ because otherwise alternating between cooperation and defection would lead to a higher payoff than mutual cooperation. The winner of an IPD game is determined by summing up each player's payoffs over the rounds played. During the IPD, players memorise outcomes of past PD rounds. A strategy in the IPD is a decision rule that uses this knowledge to derive the decision for the next turn.

A typical strategy in the IPD is e.g. ALLC, meaning that a player will always choose C. Another classical strategy is TFT ("tit-for-tat") i.e. to cooperate on the first move and mimic the opponent's move for all subsequent moves. The performance of the different strategies was compared in computer simulated tournaments (Axelrod, 1984; Nowak & Sigmund, 1993) where TFT outperformed all other strategies. In general, altruistic strategies tended to outcompete the greedy methods over the long-term.

Closer to real decision contexts, in IPDs players collect experience, use strategies and can e.g. reward desired behaviours of their opponents or punish unwanted ones. Nevertheless, the IPD only considers two person interactions and does not regard larger groups of decision-makers.

2.1.1.4 Social dilemmas

The PD is a two-person dilemma game. Considering three or more players yields the N-person dilemma (NPD) which is the classical game theoretic conception of the social dilemma (Dawes, 1980; Kollock, 1998; Komorita & Parks, 1995; Liebrand, 1983) that Dawes (1980) defines as follows: N players can choose to either cooperate or to defect. A player's payoff in a given round depends on his own decision and on the number of other players choosing to cooperate in that round. Assuming that D(m) is the payoff for defection if m other players cooperate and C(m) is the respective payoff for cooperation. Then a social dilemma is given if

(a) $D(m) > C(m+1)$ for $m < N$ and

(b) $D(0) < C(N)$

Condition (a) means that defection always leads to higher individual payoff than cooperative behaviour while (b) states that defection by all players yields lower payoff than cooperation by all. The game theoretic implication of condition (a) is that uniform defection is a Nash-Equilibrium because no single player would be better off by switching behaviour. However, condition (b) implies that the payoff of the equilibrium is dominated by the outcome of uniform cooperation. Therefore, in terms of game theory, an N-person dilemma is characterised by the existence of a dominating strategy for all players that results in a deficient equilibrium. In economics this deficient equilibrium is referred to as a Pareto suboptimum.

The transition from two-person to N-person dilemmas has some notable effects on the dynamics of the game which can be summarised as three important observations (Dawes, 1980; Kollock, 1998): Firstly, in the two-person dilemma each player exactly knows the behaviour of his opponent while in the N-person case a player's actions are not necessarily perceivable by the others. Due to this anonymity free-riding of an individual will not be fully noticed by others. Secondly, the cost that such free-riding imposes on others is diffused throughout the group in an N-person dilemma. In the two-person case cost from defecting is focused completely on one's partner. Finally, in a repeated two-person dilemma, each player can substantially influence the other's outcomes providing a means to influence his opponent’s choice of behaviour. In contrast, in an N-person dilemma, a single player has little or no direct influence on the outcomes that others achieve.

2.1.1.5 Empirical evidence

Evidence of social dilemmas in real life abounds (Dawes, 1980; van Lange, Liebrand, Messick, & Wilke, 1992). Commonly two general categories of social dilemmas are distinguished. Public good dilemmas (Ernst, 2001; Olson, 1965; Suleiman, 1997; van Lange et al., 1992) focus on the production of a joint good. Such public goods are defined by two features: collective provision and non-excludability from the benefits of the public good. Hence, the social dilemma arises when individual members of a providing group decide whether to contribute to the public good provision (to cooperate) or whether not to contribute and only enjoy the benefits of the public good (to defect).

In contrast, the commons or resource dilemma (Ernst, 2001; Hardin, 1968; Ostrom, Gardner, & Walker, 1994) focuses on a structurally equivalent decision situation where individuals have open access to a common but bounded resource. Here, cooperative behaviour enables sustainable use of the resource whereas defective behaviour may lead to overuse and ultimate destruction of the resource.

Common to both types of social dilemma is that the risk of deficient outcomes is given by what economists call externalities which exist “whenever the behaviour of a person affects the situation of other persons without the explicit agreement of that person or persons” (Buchanan, 1971, p. 7 quoted by Dawes, 1980). The exact character of such externalities defines the structure of the social dilemma, i.e. “the rules of the game”.

Public goods are defined by a production function that relates individual contributions to the level of the public good (see Kollock, 1998, p. 190 for some typical function shapes). Moreover, public goods are nonrival, i.e. the benefits one person gets from the public good do not decrease the benefits available to others.

In contrast, commons are characterised by the subtractability of benefits, i.e. the possibility to obtain benefits from the commons where the extent of the individual benefits depends on the extractions by others. Furthermore, commons are defined by a carrying capacity that reflects the rate with which the common resource pool is renewed.

In both dilemma cases the core problem feature is non-excludability of a joint resource. Numerous real-world examples exist where exclusion of others is barely feasible, expensive or even impossible (Ostrom et al., 1994).

Game theoretic analysis yields for both classes of social dilemmas that defection is the dominant strategy under the given incentive structure. For the case of resource dilemmas this deficient equilibrium of collective defection is illustrated by Hardin's concept of the tragedy of the commons (Hardin, 1968). The game theoretic predictions as well as Hardin's pessimistic view are challenged by a body of empirical studies (most prominently Ostrom, 1990; Ostrom, 2003) that document the prevalence of cooperative behaviour in the form of collective action (Olson, 1965).

The central topic of research on social dilemmas is the identification and the understanding of mechanisms that trigger, drive or enable the observed cooperation and therefore resolve the social dilemma. There is a comprehensive body of research that approach the problem empirically by laboratory experiments (e.g. Dawes, 1980; Messick & Brewer, 1983; Poteete, Janssen, & Ostrom, 2010), by case study analysis (e.g. Poteete et al., 2010; Ostrom et al., 1994) or more recently by combinations of the latter two (for an up-to-date overview see Poteete et al., 2010). A current overview of contributions from social psychology is given in Kramer, Tenbrunsel, and Bazerman (2010). The comprehensive body of research from experimental economics is overviewed in Ledyard (1995) and the more recent update Vesterlund (2012).

2.1.2 Factors influencing cooperation

This section draws on providing a systematic overview of the factors that drive or inhibit cooperation in commons and public good dilemmas.

Most of the early research following Dawes' seminal work focused (more narrowly) on solutions to social dilemmas, i.e. the identification of leverage points to intervene in social dilemmas in order to promote cooperation. The majority of this branch of work is based on human subject experiments. Commonly, three classes of solution approaches are considered (Kollock, 1998): Focusing on the reasoning of the individual actor in a social dilemma we talk about (1) motivational solutions and (2) strategic solutions. These solution approaches differ in whether they regard the actor as purely motivated by self-interest or not. In approach (2) it is assumed that the selfish actor reasons about strategic behaviour in order to maximise his outcome while in approach (1) actors are thought to adjust their behaviour with regard to the outcome of other actors. In contrast, structural solutions (3) draw on changing the externalities of the social dilemma (e.g. incentive structures) such that cooperation is fostered.

For this direction of research on eliciting and understanding mechanisms that are effective in triggering cooperation in social dilemmas there exists a wide-ranging body of experimental studies mainly from social psychology, economics and sociology (see e.g. reviews in Kramer et al., 2010; Ledyard, 1995; Poteete et al., 2010). In summary these studies provide a comprehensive set of different perspectives i.e. parts of a big puzzle. However, "theoretical integration has proven elusive" (Foddy, 1999, p. 14).

A promising step towards a theoretical framework, that integrates laboratory findings as well as evidence from case studies, is given in Kopelman, Weber, and Messick (2003) and its extension (Weber, Kopelman, & Messick, 2004). We concentrate on the earlier classification scheme (Kopelman et al., 2003) that identifies nine types of independent variables that the authors found to cover the majority of the relevant literature. The classification is mainly an ontology that groups the factor types in a hierarchical manner (see Figure 1). Here, we will not discuss the ontology as such. We will rather go through all the categories in order to provide a sufficiently complete overview of the relevant factors.

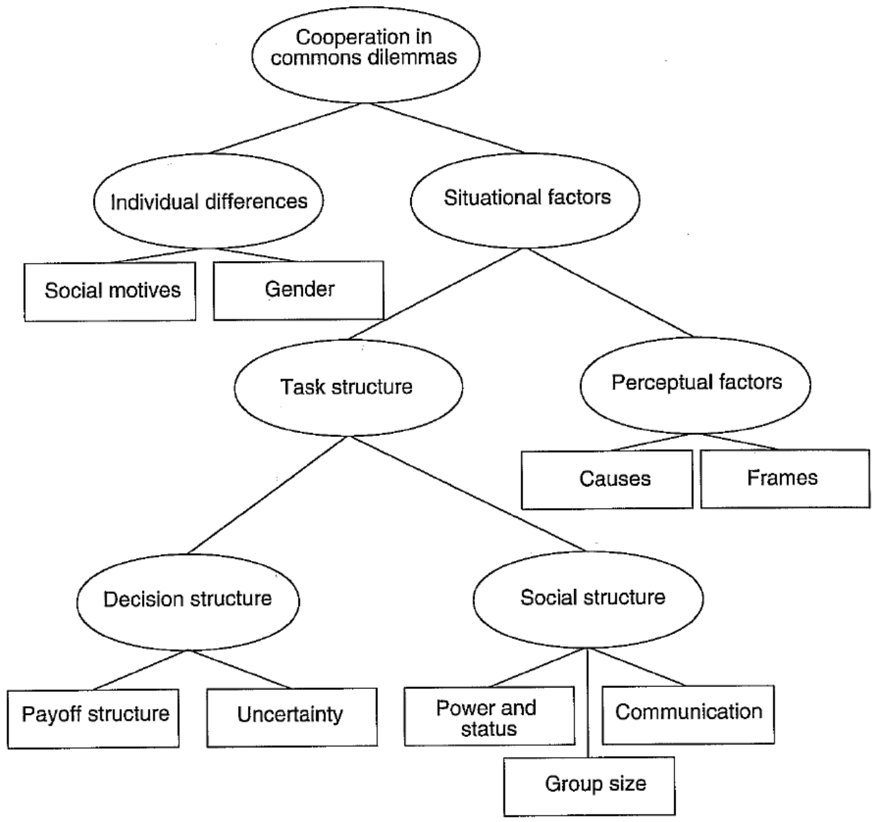

Figure 1. Elements influenceing cooperation (taken from Kopelman et al., 2003, p. 116).

The top-level categories differentiate between factors pertaining to the individual properties of the actor in a social dilemma (*individual differences*) and to external factors specifying the situational characteristics of the respective dilemma (*situational factors*). In terms of the involved solution concepts these broad categories correspond to motivational and strategic solutions, and structural solutions respectively.

The situational factors are further subdivided into factors concerning structural aspects of the dilemma (*task structure*) and factors pertaining to the individual perception of the dilemma (*perceptual factors*). Factors relating to the structure of the dilemma are additionally split into factors describing the dilemma-related decision context (*decision structure*) and factors covering the social context of decision-making (*social structure*).

The following subsections report briefly on each of these mayor factor groups that Kopelman, Weber, and Messick (2003) identify in their review.

2.1.2.1 Individual factors

The most comprehensively studied individual factor is summarised under the concept of social value orientations or social motives (Balliet, Parks, & Joireman, 2009; Liebrand & McClintock, 1988; Messick & McClintock, 1968; Weber et al., 2004). Social value orientations are understood as stable individual traits in terms of "preferences for a particular distribution of outcomes to oneself and others" (van Lange et al., 1992, p. 17). Operationally, social value orientations are formalised as an outcome transformation that includes two dimensions: the weight assigned to payoffs for oneself and the weight assigned to payoffs for others. By varying the ratio of the weights of the two dimensions various different types of decision-makers may be parameterised. Among the large number of orientations the model allows for, the two most frequently considered are altruism (high weight put on others outcome and low weight on own outcome) and individualism (high weight on own outcome and low weight on others outcome). Altruists are sometimes also termed prosocials; individualists are also called proselfs.

In the laboratory it was shown that prosocials compared to proselfs give more to others in game representation of social dilemmas (e.g. McClintock & Liebrand, 1988). Other studies from outside the laboratory showed e.g. that prosocials invest more in personal social relationships (van Lange, Agnew, Harinck, & Steemers, 1997) or tend to give more money to charitable causes (van Lange, Bekkers, Schuyt, & van Vugt, 2007) when compared to proselfs.

Other individual factors influencing cooperation comprise e.g. gender, focusing on the general view that more females exhibit prosocial behaviour than men (Balliet, Li, Macfarlan, & van Vugt, 2011), or personal experience reflecting the "potential of personal histories and experiences to shape understandings of a situation and consequent behaviour" (Weber et al., 2004, p. 289). However, theories on the latter two factors generally stress the strong additional influence of situational characteristics and are much weaker in terms of their experimental founding compared to social value orientations. While the concept of social orientations is still widely used in empirical social psychology (e.g. Bridoux, Coeurderoy, & Durand, 2011; van Lange, Klapwijk, & van Munster, 2011) it is "not very useful as a solution to dilemmas (…) [because it] (…) does not tell us how to increase the level of cooperation"

(Kollock, 1998, p. 193). However, social orientations provide an empirically founded and lean way of representing and modelling individual differences in the preferred distributions of outcomes from social dilemmas.

2.1.2.2 Decision structure

The rules that relate individual behaviours to payoff are crucial in social dilemmas. It is well established that changing the ratio between economic payoff for cooperation and payoff for defection (e.g. in terms of sanctions) has strong influence on cooperation rates (van Lange et al., 1992, pp. 14–15). This purely economic dimension is known to be complemented by a dimension that reflects social approval or disapproval of behaviours (Gächter & Fehr, 1999). For instance adverse sentiments towards free riders may eventually result in altruistic punishment like penalties or exclusion from the benefit of a public good (Fehr & Gächter, 2002; Janssen, Holahan, Lee, & Ostrom, 2010).

However, these two dimensions of payoff are subject to uncertainty. It is common to distinguish between social and environmental uncertainty in social dilemmas (van Dijk, Wilke, & Budescu, 2004). Social uncertainty refers to the anonymity in social dilemmas, i.e. the lack of knowledge about and the unpredictability of the behaviour of others in the dilemma situation. Environmental uncertainty broadly refers to the lack of full knowledge about important parameters of the dilemma's structure (van Dijk et al., 2004). In the context of social dilemma research the two most commonly stated environmental uncertainties pertain to the size of shared resource (public good or common-pool resource) and to the provision or extraction threshold necessary to produce or maintain it. Kopelman, Weber, and Messick (2003) conclude in their review that in general terms reducing uncertainty by providing scientific facts e.g. on the characteristics of the shared resource increases cooperation. Nevertheless, there exist notable exceptions (Kopelman et al., 2003, p. 127).

2.1.2.3 Social structure

Three dimensions are usually considered when investigating the influence of social structure on decision-making in social dilemmas: Group size, power or status relations between group members, and communication between group members.

The understanding that small groups exhibit higher levels of cooperation compared to larger groups is well established in social dilemma research (Dawes, 1980; Olson, 1965). One early explanation approach for this small-group-effect was that in small groups, individuals feel more able to personally make a difference in the group's outcome. This observation fits in the framework of self-efficacy (Bandura, 1986). Other results on the effects of group size are e.g. summarised in Weber, Kopelman, and Messick (2004) who conclude that group size has to be seen as a "salient situational cue that has noteworthy effects on the conclusions people reach about appropriate behaviour in social dilemmas" (Weber et al., 2004, p. 297).

A similarly stable and classical result from social dilemma research is the appointing of a leader as a possible solution to social dilemmas (Hardin, 1968). Circumstances under which leaders are appointed are e.g. situations where the management of a common resource is perceived as difficult and when effects of overuse are experienced (Samuelson, 1991). In lab experiments it was shown that leaders receive social appraisal from followers when they are successful (Wit, Wilke, & van Dijk, 1989). Furthermore, recent results from experimental economics indicate that in particular voluntary leadership increases cooperation rates in public good dilemmas (Rivas & Sutter, 2011).

Group size effects as well as leader appointments are based on underlying communication processes between group members. The effect of increased communication on cooperation rates has frequently been studied and it is typically concluded that communication effects are robust (for reviews, see Ledyard, 1995; Weber et al., 2004). Explanations for the effects are manifold but fall into two general types: social utility and social commitments. The social utility explanation draws on the fact that communication increases the utility of collective, in relation to individual, outcomes by increasing feelings of group identity or by stressing social norms that reinforce cooperative behaviour. The social commitment explanation is that communication gives the opportunity to make explicit or implicit agreements that individuals later feel obligated to.

2.1.2.4 Perceptual factors

People decide in a social dilemma based on their observation and their understanding of the situation they find themselves in. Factors that influence such individually subjective perceptions fall broadly in two different categories (Kopelman et al., 2003, Weber et al., 2004): The first group of factors relates to causal attributions which reflect factual knowledge of the dilemma situation that is at a decision-maker's disposal. The second group of factors pertains to the subjective framing of outcome alternatives that is used by a decision-maker to assess behavioural options in his subjective reference system.

Causal attributions comprise e.g. knowledge on the scarcity or abundance of a shared resource. This “resource knowledge” (Ernst, 1997) is actively utilised by individuals and reduces resource uncertainty. Other causal attributions reflect knowledge of the interrelation between the state of a shared resource and the behaviour of other resource users. Early work showed in the context of resource dilemmas that individuals behave differently if they believe that resource scarcity is an objective property of their environment or if they attribute resource scarcity to the harvest behaviour of other members of their user group (Rutte, Wilke, & Messick, 1987). In general, the availability of causal knowledge seems to influence the willingness to engage in structural solutions of social dilemmas (Samuelson, 1991).

Another set of important perceptual factors is summarised under the concept of framing. The theoretical roots of framing originate from prospect theory (Kahneman & Tversky, 1979). Applied to the context of social dilemmas prospect theory proposes that individuals assess outcomes from their behaviours differently depending on whether they appear to them as gains or losses. As a general pattern, people exhibit some degree of loss aversion, i.e. a preference that favours outcomes labelled as gains over outcomes described as losses. Clearly, an outcome framing as losses and gains corresponds well to the notions of “giving” in a public good dilemma and “taking” in a resource dilemma. However, studies on this correspondence “found inconsistent and puzzling results” (Kopelman et al., 2003, p. 140). Nevertheless, it can be shown that the reference point defining outcome frames can shift due to individual differences or that it can be actively moved by external intervention. For example people's perception of social dilemmas varies when they are described using different metaphors (Allison, Beggan, & Midgley, 1996). Likewise, cooperation rates in experimental dilemma setups were show to be strongly influenced by way the game is presented to the test persons, i.e. the “name of the game” (Liberman, Samuels, & Ross, 2004).

2.1.3 Synthesis I: Systems overview

The purpose of this concluding section is to summarise the main relevant findings of empirical and theoretical social dilemma research. In particular, we will provide an integrated systems view on individual decision-making in public good dilemmas that aims at structuring the relevant entities in a nested and coupled way. Section 2.1.4 will build on this systems perspective and extract the crucial drivers that influence decision-making in social dilemma situations.

The literature review of the previous subsections was organised along a chronological timeline: Starting out from the historical roots given by variants of the classical prisoner's dilemma game and their conception in mathematical game theory we concluded with the influential game-theoretic definition of a social dilemma by Dawes that links the research branch to psychological questions. Furthermore, Dawes' definition clearly frames the case of public good dilemmas, which is the core of this dissertation, as one instantiation of a social dilemma. The second prominent case of a social dilemma is given by the resource dilemma, which is in many aspects equivalent to the public good dilemma. The main structural distinction between the two cases lies in the characteristic of the shared resource considered: A public good is defined by a production function that immediately reflects contributions by the members of the providing group in the level of the good. In contrast, the resource dilemma has an explicit time dimension reflecting the rate by which the common resource regrows. In addition, public good and resource dilemmas are not necessarily equivalent from a psychological point of view when focusing on the individual decision-maker and his respective framing of contributions in the public good dilemma compared to extractions in the resource dilemma (Kahneman & Tversky, 1979).

The fundamental subject of research on social dilemmas is to provide an understanding of the mechanisms that enable altruistic cooperation in situations where individual rationality should inevitably lead to collective defection. It is the aim of this dissertation to bring forward this research tradition for the case of public good dilemmas. In doing so we reviewed some of the most relevant empirical findings along the theoretical framework of Kopelman, Weber, and Messick (2003).

One main message from the theoretical framework is on the provided grouping of the multitude of factors which scholars have identified. The two main perspectives on these factors regard the heterogeneity of actors in a social dilemma and the situational embedding of individual decision-making. While this notion of embeddedness is well in line with the targeted nested systems view, the subcategories that specify the situational context stress the viewpoint of laboratory experiments: How is the structure of the dilemma *set up* and in what way is the perception of this structure *facilitated*? In contrast to this view, we argue that the situational context of decision-making consists of a multitude of different more or less linked sub contexts. Individuals decide within these sub contexts and their actions influence the state of their contexts in a simultaneous way. In general, each context is a dynamical system characterised by its particular structural properties and its spatial-temporal dynamics. However, from the perspective of individual agents some of these properties and dynamics may turn out be equivalent to the payoff structure of a social dilemma. Thus, we recognise social dilemma structures as meta-properties which emerge from the interaction of individuals with their external contexts on the one hand, and from the complex dynamics governing the temporal and spatial development of these contexts on the other hand.

Figure 2 illustrates this notion for the case of public good dilemmas. The left side of the figure shows the spatial context in which a public good is provided and in which its benefits become accessible. In order to capture spatial heterogeneity, it is assumed that diverse public goods exist or emerge on fixed locations in a common environmental context. It is further assumed that each public good has a fixed spatial extent defining the area where contributions are accumulated and where benefits may emerge. As a simplification the extents of the public goods do not overlap spatially. Environmental uncertainty is reflected by assuming that the public goods are sensitive to external conditions, i.e. irrespective of the contributions to the provision the obtainable benefit may vary spatially and temporally. In the context of section 2.1.2, the described facets of spatial heterogeneity and uncertainty of the public goods allow representing important structural (see section 2.1.2.2) and perceptual (see section 2.1.2.4) factors of the social dilemma in bottom-up manner.

The right side of Figure 2 illustrates the social context of the individuals providing the public goods. It is distinguished between two structural components. Firstly, individuals are embedded in a common network of social influences where individuals are vertices (shown as small circles) that are linked by network edges (shown as arrows). Secondly, non-overlapping groups of individuals are formed. Each group is linked to one public good in the environmental context. The contributions of the group members provide the respective public good. Furthermore, individuals obtain a perceptual feedback from the environment which includes the success of the public good provision and local perceptions of other external conditions. The described notion of the social context of decision-making allows representing social-structural (see section 2.1.2.3) and perceptual (see section 2.1.2.4) factors influencing cooperation in social dilemma situations. For instance, communication structures or power relations can be represented in the topology of the social network and their local perception by the individuals.

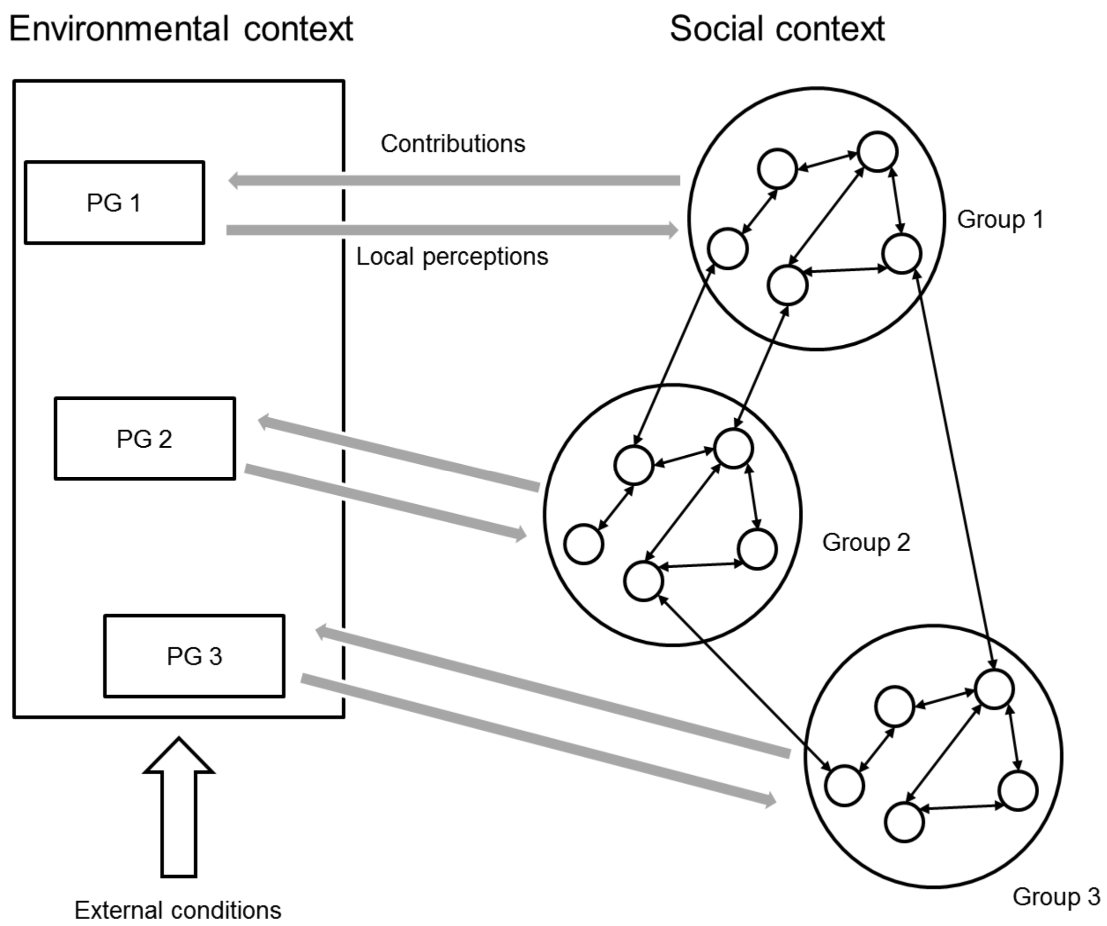

Figure 2. Systems overview of public good provision. It is distinguished between the environmental and social context of public good provision. Public goods are provided by groups of actors. Each public good (PG) has a location and a fixed spatial extent in the environmental context and is provided by a distinct actor group in the social context. In addition, actors are embedded in a common social network. For illustration purpose, three public goods and three providing groups are shown, while arbitrary numbers are possible.

The individual factors (see section 2.1.2.1) influencing behaviour in a public good dilemma are represented in the actor concept that is illustrated in Figure 3. Actors process local perceptions from the environmental and social context in order to derive actions to be forwarded to their environments. This process of action selection is driven by the actor's subjective preferences. Preferences are understood as individual traits that relate an actor's preferred means to his desired ends. Hence, decision-making is highly subjective (at least)

because of (a) the local character of the perceptions, (b) perceptual differences (e.g. framing), and (c) other subjective preferences (e.g. social orientations).
For the purpose of the systems overview the process of action selection remains a black box. We will shed more light on this process of individual decision-making in section 2.3.

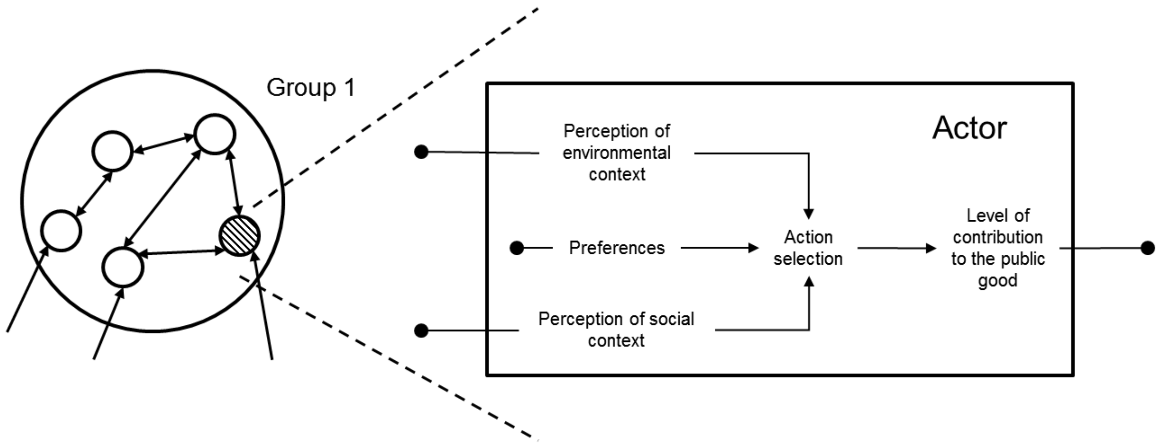

Figure 3. Individual perspective of public good provision. Based on its perceptions from the environmental and social context, and guided by individual preferences, an actor decides on his contribution to the public good.

2.1.4 Synthesis II: Requirements A to D of research method

This section aims at condensing the results from the literature review and the systems analysis by stating the essential drivers that influence decision-making in social dilemmas. Any model of individual decision-making in social dilemmas and thus in public good dilemmas has to account for these aspects in a sufficient way. Accordingly, we formulate four core structural aspects that a suitable research method has to consider:

Requirement A: Individual perspective

Obviously, humans base their decisions on some notion of utility with respect to their subjective preferences. In addition to striving for personal gain, these preferences cover dimensions like social value orientations (Liebrand & McClintock, 1988; Messick & McClintock, 1968), inequity aversion (Fehr & Schmidt, 1999), reciprocity (Fehr & Gächter, 2000; Gintis, 2000), social norms, moral considerations and the like (Dawes, 1980). In sharp contrast to the classical game theoretic view, individuals are recognized as boundedly rational decision-makers (Simon, 1955) that process limited knowledge with limited cognitive effort. However, individuals can be seen as mostly rational and consistent within the scope of their knowledge, processing capabilities and preferences (Ernst, 1994).

Requirement B: Spatial embedding

All individual decision-making is embedded in a spatial context. This environmental context is highly heterogeneous e.g. in terms of accessible resources or spatially distributed sources of danger or opportunities. The composition of such environmental properties can constitute social dilemmas or at least distinctly influence decision-making in other social dilemmas. In summary, the spatial embedding accounts for the environmental variety we observe in real life (Ernst, 2009).

Requirement C: Social structure

The structure of a social dilemma is supplemented by the social structure that individuals are part of. Social structure is understood as the "thick network of social interactions" (Gardner & Stern, 2000, p. 150) that is found to be conductive to the resolution of social dilemmas in many cases. E. g. appointing a socially accepted leader personality (van Dijk, Wilke, & Wit, 2003) or social coordination (Kopelman, 2009; van Dijk & Wilke, 1995) can help to overcome social dilemmas. The essential understanding is that individuals possess and utilise social knowledge in social dilemma situations (Ernst, 1997, p. 37).

Requirement D: Temporal and spatial dynamics

In addition, individual decision-making is embedded in a temporally and spatially dynamic context. Processes like collecting experience or learning require the explicit consideration of a time dimension. In social dilemmas the temporal trap (Messick & McClelland, 1983) is an essential problem feature that describes the conflict between individual short-term gain and collective long-term loss especially in the commons dilemma context. In addition, social dilemmas can often be characterised by a spatial trap (Ernst, 2001) drawing on the conflict between local gain and distant loss.

Although human lab experiments provide comprehensive insights into the factors affecting behaviour in social dilemmas, direct translation of these results towards everyday life is by no means obvious. For example Jager, Janssen, Vries, Greef, and Vlek (2000), p. 361 stress that test persons recognise the artificial character of lab situations and understand that their behaviour in the lab does not have far-reaching implications in their real world, while decision-making in real-life social dilemmas can have striking impact on one's personal future circumstances of living. Likewise, field studies inform about a very specific and narrowly defined situation context and general causal relations between factors cannot be easily understood from the observations.

While especially requirement D stresses the importance of dynamical aspects, the classical empirical approach is rather static in nature. The temporal context of psychological or economic experiments is usually hours, while behavioural feedback from real-world social dilemmas can have a scope of decades (especially in an environmental context). Furthermore, validation of inferred theories, in terms of the dynamics they imply on the level of individual behaviours and cognitions as well as in terms of macro level collective behavioural patterns, is largely missed out by the classical empirical approaches.

All these deficits of the classical approach are tackled by applying modelling and simulation. The following section introduces the method of agent-based social simulation (ABSS) and shows that the approach satisfies requirements A to D.

2.2 *Agent-based social simulation in the domain of social dilemmas*

This section is about ABSS, which is the key methodical approach of the dissertation.

The first subsection 2.2.1 prepares the ground by giving a general introduction to ABSS. In a following synthesis section 2.2.2 we briefly discuss the approach as such and relate it to the demands of the application domain of public good dilemmas. In particular, we link the core concepts of ABSS to the systems overview derived in section 2.1.3 and motivate that the method is a suitable way to account for the mandatory requirements formulated in section 2.1.4.

Subsection 2.2.3 sets the focus on existing ABSS exercises in the area of social dilemmas. In addition to giving a compact and structured overview of existing models, the objective of the section is to identify the important properties of modelling approaches that draw on a medium level of abstraction in a psychologically sound way. A following synthesis section captures conclusions by formulating two additional ABSS-related requirements of the research method.

2.2.1 Overview of agent-based social simulation

The purpose of this section is twofold: Firstly, we briefly introduce ABSS. A more focused overview on ABSS of social dilemmas is given in section 2.2.3. The second objective of this section is to link ABSS to the methodical requirements formulated in the previous section by outlining the potential of ABSS in the field of public good dilemmas (section 2.2.2).

2.2.1.1 Historical roots

During the last 20 years ABSS has become an important method in the field of modelling and simulation (Gilbert, 2008; Railsback & Grimm, 2011) and is a vivid field of on-going research (see e.g. The Journal of Artificial Societies and Social Simulation, http://jasss.soc.surrey.ac.uk/JASSS.html). Historically and technically ABSS builds on foundations from distributed artificial intelligence that scrutinises on the relation between macro-level phenomena and complex micro-level interactions of autonomous software agents (Weiss, 2001). Unlike other computer modelling methods like e.g. System Dynamics (Bossel, 2004; Forrester, 1971; Meadows et al., 1974) that adopts a dynamical systems perspective on observable macro-level patterns and processes, ABSS explicitly recognises macro-level patterns as emerging from complex micro-level agent interaction. Agents represent human or institutional decision-makers in psychological terms or actors in social science terms.

2.2.1.2 Agents

On the micro-level ABSS considers autonomous agents (Gilbert, 2008; Wooldrige & Jennings, 1995). Agents can perceive objects and agents in their outside world and react to changes in external conditions by executing behaviours. Agents can communicate and collect information. These external stimuli are mostly complemented by an internal state of the agent comprising mental constructs like memories, goals, or intentions. Agent decisions are based on internal decision rules which relate external stimuli and internal state to an action. Such rules can be simple reactive condition-action-rules (stimulus translated to response) or more elaborate heuristics that are activated depending on an external situation which is in line with insights from experimental social psychology (Gigerenzer & Selten, 2001; Gigerenzer et al., 1999). More complex decision-making is based on planning processes that compare alternative courses of action prior to execution and select actions which are expected to be most beneficial with respect to an agent's goals.

Agents are understood to be embedded in an outside world. It is useful to distinguish between the simulated social structure that an agent is part of, and the environmental context of an agent.

2.2.1.3 Social structure

Agents are embedded in a social structure which provides the agents with an infrastructure for social interaction and social exchange. Generally, such social influence is built upon the notion of social embeddedness (Granovetter, 1973, 1985), i.e. the understanding that an individual's opinion is influenced by the prevailing opinions within the network of social relations that the individual is part of. Here, the term "opinion" is used in very broad sense representing some attribute of an individual that is exposed to its social network peers (for the conception of social influence in social psychology cf. section 2.3.2). Such attributes typically reflect e.g. observed behaviours, the affinity to political parties or preferences for consumer goods. General opinion dynamics (Friedkin, 1998; Latané, 1981) assumes that individuals are exposed to social influence towards or against certain opinions through the ties of their social network (Barabási, 2002; Wasserman & Faust, 2009; Watts, 2003). It is further supposed that this field of social influences permanently exists and is updated as opinions change and that the influences are only limited by the structure of the social network, which may underlie temporal dynamics.

In the ABSS literature there is a multitude of work on the dynamics of opinion formation in populations as a result of agent-to-agent interaction through simulated social processes. The spectrum of models of binary opinion dynamics ranges from the very abstract (equation-based) models of "Sociophysics" (Galam, 2008, Galam, 1999; Sobkowicz, 2009) to Cellular automata-based models (Galam, 1999; Latané, 1996; Latané & Nowak, 1997; Stocker, Cornforth, & Bossomaier, 2002; Stocker, Green, & Newth, 2001). More recently Social Judgment Theory was used to further formalise effects of social assimilation and rejection on the decision-making process in a psychologically sound way (Jager & Amblard, 2005). Case study based integrated models investigate e.g. the spread of water use innovations through social networks (Schwarz & Ernst, 2009) or analyse social networks as an important driver of processes of social mobilisation (Krebs, Elbers, & Ernst, 2008; Krebs et al., 2011).

2.2.1.4 Environmental context

While the simulated social structure enables the interaction and exchange of agents through social networks, the environmental context is a non-acting but temporally and spatially dynamic representation of agents' external conditions (biophysical, natural environments, socioeconomic environments, political, legal or economic boundary conditions). It serves as a container of objects which an agent can perceive and interact with. Typically, obstacles and sources of energy (Epstein & Axtell, 1996), road maps and city districts (Power, 2009), residential housing patterns (Haase, Lautenbach, & Seppelt, 2010), hydrological dependencies along flood protection channels (Krebs et al., 2008) or spatial locations of households (Krebs et al., 2011; Schwarz & Ernst, 2009) are represented. Opposed to the network topology of social structure, the environmental context is characterised by a geographic topology and agents are embedded by assigning them spatial coordinates. This embedding provides agents with subjective perceptions and opportunities of behaviour and is thus an important source of agent heterogeneity.

Agents act as a link between different (levels of) environments. Furthermore, subjective perceptions may also be communicated across social networks. Therefore, receiving these types of messages is to be seen as a kind of mediated perception of environments in the sense of informational influence (Deutsch & Gerard, 1955), i.e. the tendency to accept information from others as evidence of reality.

In addition, the complexity of the agent's environmental context is an essential driver of complex behaviour and emergent social complexity. For instance it was shown that the repertoire of actions learned by evolutionary adaptive agents mirrors complex properties of their environment (Krebs & Bossel, 1997).

2.2.2 Synthesis III: The potential of agent-based social simulation in the domain of social dilemmas

The ABSS definition given in this section fits neatly into the systems overview shown in Figure 2: Agents are per definition seen as subjective entities (cf. Figure 3). Furthermore, they exhibit clear notions of embeddedness in social and environmental contexts, and various interaction levels are transparently specified. Finally, the formulated requirements (section 2.1.4) can in principle be met:

- **Relevance to requirement A:** The agent definition given in section 2.2.1.2 naturally accounts for the requirement to represent the individual decision-maker's perspective: Agent attributes do represent heterogeneous preferences of decision-makers in an explicit and descriptive way. Therefore, it is possible to link constructs like utility and psychological behavioural theories. Bounded rationality is implicitly included: Agents possess bounded, local and contextualised knowledge about their surrounding world and use limited cognitive resources. Rather, it is challenging to the modeller to enhance the cognitive capabilities of the agents such that they behave reasonably similar to real decision-makers (Gilbert, 2008, pp. 15–16).
- **Relevance to requirements B and C:** Social structure is an essential component of ABSS, in particular the modelling of social networks. These define the boundary

conditions of successful collective action, lock-in of specific behaviours or social coherence, i.e. the social confirmation and reinforcement of behaviours by social interaction. In addition, in such social environments social norms or institutions can explicitly be represented or they can be observed as emerging macro-level properties. Likewise requirement C is met because the environmental context provides for the agent's spatial embedding. The environmental context can be represented by a coupled model of the external world of an agent that represents the application-specific situation aspects in a dynamic way including possible social dilemma characteristics.

- **Relevance to requirement D:** The explicit consideration of temporal dynamics is essential to any simulation exercise. Particularly in ABSS, agents use past events or sequences of events observed in their environments to derive their decisions. Temporal sequences and coincidences play an important role. Spatial relations and dynamics are covered by the simulated environmental context to the extent relevant to the application context. Therefore requirement D is met.

In summary, it has to be noted that the purpose of ABSS and modelling in general is not mere prediction of future developments by simulation. Epstein (2008) nicely states "Sixteen Reasons Other Than Prediction to Build Models" among which the most essential are to provide a qualitative understanding of dynamics, to identify uncertainties, to question existing theory and inspire new theory building. Finally, the descriptive transparency and richness of the method stimulates and simplifies stakeholder dialog.

Clearly, these objectives of ABSS match well interesting research questions on social dilemmas like e.g.: How do heterogeneous populations manage cooperation depending on their composition? How do fluctuating boundary conditions influence cooperation rates over time? How well do theories on cooperation in social dilemmas perform if the dilemma structure slightly deviates from the stylised conditions set up in laboratory experiments?

2.2.3 Agent-based social simulation research on social dilemmas

The previous section introduced ABSS and stated the method's compatibility with the requirements formulated earlier, thus clearly qualifying ABSS as a suitable approach to investigating public good dilemmas. However, until now, we have been less tangible about distinctive properties of generic, middle-range agent-based models. In tackling this issue, we start by giving a classification scheme that provides dimensions to assess possible candidate modelling approaches (subsection 2.2.3.1). Subsequently, we compare existing ABSS modelling exercises in application contexts involving a social dilemma along the classification scheme. Finally, in a synthesis section, we formulate the derived additional requirements of the ABSS approach of the dissertation, namely the medium level of abstraction and grounding in psychological theory (subsection 2.2.4.).

2.2.3.1 A classification scheme

A useful way to classify ABSS applications in the field of social dilemmas is to compare approaches along the spectrum of “thin simulations” and “thick simulations” (Kliemt, 1996).

Thick simulations are strongly founded in empirical data from a very narrow application context and draw on providing very specific answers to specific questions. The scope of such modelling exercises is not to provide generalizable results that may be extrapolated to other application contexts. Usually thick simulations focus on the representation of few cognitively rich subjects.

Thin simulations are mainly grounded in existing theory of an application domain. Such simulations are much more in the spirit of Epstein (2008) in that they provide a means of testing, questioning and extending theory. Case specific or even quantitative validity is not the scope of such modelling exercises. Generally, types of subjects are found to be relevant and simulations represent large numbers of subjects that are instances of the types identified.

While the classification from thin to thick simulations goes back to philosophical considerations that are in principle relevant to any modelling and simulation exercise, more recently, as ABSS simulations matured, the community focused on an additional dimension that covers different methods of empirical founding. The influential paper on this topic is Janssen and Ostrom (2006) on the empirical founding of ABSS from the perspective of social-ecological systems. This perspective naturally recognises social dilemmas as a core feature of agent decision-making and is therefore relevant to the problem domain of this dissertation.

Janssen and Ostrom (2006) identify and discuss four principle approaches to empirical grounding of ABSS:

In application domains where comprehensive sets of observational data are available (e.g. markets or the Internet), modelling-relevant situation characteristics can be described by stylised facts like e.g. derived statistical measures and distributions, or other macro-level observations. Simulations are then used to search for the micro-level rules that can generate the stylised facts. Mostly, such simulations use simplistic, equation-based agents. Examples are from economics (Axtell, 1999), political science (Cederman, 2003), or sociophysics (Galam, 2008).

A second approach of empirical grounding focuses on eliciting data on human decision-making by conducting human subject experiments in highly abstract, controlled environments (which to a degree disregards context-related issues). This data is then used to validate simulation models and underlying hypothesises. The approach is largely used in economics (Duffy, 2006) and also in social-ecological contexts (Janssen et al., 2010).

A third approach is role-play and companion modelling. In this approach stakeholders are directly involved in data elicitation, model building and validation. In a lab-like situation, stakeholders play a role game reflecting the situation characteristics of the problem domain. Based on the observation of this game, modellers build the ABSS, which is then brought back to the stakeholders, discussed and refined. Examples in the area of resource dilemmas are from the French school around Olivier Barreteau and are implemented by using the CORMAS framework (Barreteau, Bousquet, & Attonaty, 2001; Barreteau, Le Page, & D'Aquino, 2003). Likewise strongly based in stakeholder dialog but not involving role-play is the approach of the Centre for Policy Modelling in Manchester (Alam, Meyer, Ziervogel, & Moss, 2007; Geller & Moss, 2008).

Finally, approaches grounded in statistical case study analysis are based on (rather rich) empirical datasets for a given case (survey, census, field observation, remote sensing). Examples exist from land-use change modelling, agricultural economics, and electricity markets. Model parameterizations are validated against the data. Typically, such approaches investigate (policy) scenarios (see e.g. Berger & Schreinemachers, 2006; Berger, Schreinemachers, & Woelcke, 2006; Krebs et al., 2011; Schwarz & Ernst, 2009; Wilson, Yan, & Wilson, 2007).

All four approaches have been successfully applied in the context of ABSS of social dilemmas. However, the first two methods are much more grounded in theory and focus on generalizable insights while the latter two draw more on capturing characteristics of a specific case. Broadly speaking, rather thin simulations would most likely get empirical founding through methods 1 and 2 while simulations from the thick end of the spectrum would rather rely on empirical founding by methods 3 and 4.

This following subsections review some of the existing work in the field of ABSS of social dilemmas. We classify approaches along the spectrum from thin to thick simulations and relate the approaches to their respective methods for empirical founding. We aim to identify a suitable trade-off between generalizability and theoretical soundness on the one hand and context validity on the other.

2.2.3.2 Thin simulations

Most of the classical contributions of ABSS in the field of social dilemmas belong to the group of thin simulations (Gotts, Polhill, & Law, 2003). Influential, pioneering work goes back to (Axelrod, 1987, Axelrod, 1984) who initiated the famous IPD tournament and subsequently built simulations that allowed investigating the evolution of strategies by using a genetic algorithm (see summary section in Poteete et al., 2010, pp. 178–180). Axelrod's work spawned a body of research on agent-based models focusing on different versions of the IPD by adding on facets like spatial interactions, tags and partner selection, social norms, or probabilistic effects. A comprehensive review of the field is given in Gotts, Polhill, and Law (2003); for a more compact summary see Poteete, Janssen, and Ostrom (2010), pp. 178–188. Recent work in the Axelrod line of research exists e.g. on spatial aspects in PG games (Brandt, Hauert, & Sigmund, 2003; Zhang, Zhang, & Chu, 2011). In a similar vein, Roca & Helbing (2011) investigate the interplay between individual "greediness" and the emergence of social structure fostering cooperation in a PG game. In their ABSS, agents play PG games in their spatial neighbourhood on a 2-dimensional grid topology. Agents migrate to a different location if their profit from the PG game is not compatible with their greediness, which is represented as an aspiration threshold in a Win-Stay-Lose-Shift decision heuristics (Nowak & Sigmund, 1993).

Likewise acknowledging that social structure may be seen as an interaction topology in PG games (that in fact differs from spatial neighbourhood relations, see section 2.3.2.2), Spiekermann (2009) investigates the influence of dynamic social networks on cooperation rates in PG games. In his ABSS, agents can cut and create network ties and therefore shape their respective group structure. The simulations show the power of such basic mechanisms in sustaining cooperation mainly because cooperators can manage to avoid defectors and cluster with other cooperators.

Such thin simulations draw on the investigation of phenomena of complexity resulting from high levels of interaction between large numbers of agents and on the experimental refinement of existing theories. The ABSS approaches are characterised by high levels of abstraction and strongly simplifying assumptions like simplistic agents, primitive interactions, and simplified representations of agents' social and environmental contexts. Especially, when it comes to cognitive foundations of agent decision-making, thin simulations make little use of the potential of ABSS (see section 2.2.2).

The link to empirical founding is only loosely provided through qualitative stylised facts or completely neglected. For the case of public good dilemmas such stylised facts are e.g. that social exchange or social norms, and individual preferences influence the level of cooperation.

2.2.3.3 Thick simulations

The other extreme of the spectrum is given by thick simulations strictly based on case study specific evidence. In these approaches, decision-making of agents is strongly grounded in the observation of real actors and their respective environments. Examples exist dominantly in the context of natural resource management (Barreteau & Bousquet, 2000; Lansing, 1991; Le Bars, Attonaty, Pinson, & Ferrand, 2005; Rouchier, Bousquet, Barreteau, Le Page, & Bonnefoy, 2001).

The ABSS SHADOC (Barreteau & Bousquet, 2000; Barreteau, Bousquet, Millier, & Weber, 2004) is an early, classical and typical thick simulation. SHADOC investigates the sustainability of a collectively managed irrigation system based on a case study in Senegal. In the model farmer agents' decisions on their respective water withdrawals from the common irrigation systems are guided by agents' representations of individual goals, decision rules and subjective perceptions of their common environment. Agents are embedded in a (randomly initialised) social network that is used as an infrastructure for inter-agent information exchange mainly on available allowances to secure a farmer agent's financial resources. The biophysical environment of the agents is modelled spatially explicit and temporally dynamic in that it considers the feedback of water consumption behaviour to the water level of the irrigation channels and water availability.

The example of SHADOC demonstrates clearly that descriptive thick simulations make use of the typical capabilities of ABSS and also account for requirements A to D. However, theoretical embedding of the models in the context of social dilemma research e.g. in terms of a thorough structural analysis of the decision situation is largely neglected. In addition, individual decision-making is modelled in an ad-hoc and strictly case specific manner and results of relevant psychological research are mostly not taken into account.

2.2.3.4 Psychologically sound simulations

Explicit account for psychological theory of social dilemmas is rare in the field of ABSS. Gotts, Polhill, and Law (2003) only make reference to the Consumat ABSS (Jager et al., 2000). The Consumat approach is used to compare the long-term behavioural dynamics in a resource dilemma for two types of agents that differ mainly in the theoretical grounding of their respective decision-making (Jager, Janssen, & Vlek, 2002). The decision-making of the type Homo oeconomicus is represented following the rational actor paradigm of mainstream economics. In contrast, closer to real actors, agents typified as Homo psychologicus are endowed with limited cognitive resources and their decision-making integrates psychological theory on e.g. social comparison, imitation, or habits. The authors investigate the effects of different micro-level assumptions on macro-level indicators of sustainability.

Other early and more recent contributions exist that explore resource dilemmas with ABSS that explicitly include the perspective of psychology, environmental psychology, or social psychology.

The kis model (knowledge and intentions in social dilemmas; Ernst, 1994; Nerb, Spada, & Ernst, 1997) is an early psychologically sound simulation of behaviour, social interaction, and knowledge acquisition in resource dilemmas. In the kis model, agents are heterogeneous in the individual cognitive motives guiding their behaviour. Motives are represented as subjective preference structures. Furthermore, agents collect experience and accumulate resource knowledge and social knowledge. The model is well grounded in the relevant cognitive-psychological theory. Moreover, kis was applied and validated in laboratory contexts and is therefore also empirically sound.

In a similar vein, the Social-Ecological-Relevance Model (SER; Mosler & Brucks, 2003) assumes that individuals in a resource dilemma utilise ecological knowledge, i.e. subjective factual information about the resource, as well as social knowledge that is collected by information exchange over social networks. The weighting between the two knowledge components may vary dynamically depending on an individual's preferences and on the situational decision context. The model is grounded in psychological theory and it was successfully used to replicate various experimental findings (Mosler, 2008; Mosler & Brucks, 2003, p. 126).

Clearly, individual decision-making and its social and environmental embeddedness is the core element of ABSS. The research school presented in this subsection concludes that the most relevant theoretical and methodical point of reference originates from the field of psychology (including e.g. social psychology and environmental psychology). The Consumat approach accounts for the diverse groundwork contributions from psychology by proposing a multi-theoretical framework that integrates various psychological theories found to be relevant in understanding (consumer) behaviour. Furthermore, the kis and the SER approaches demonstrate how empirical methods from psychology can be integrated in ABSS exercises.

All three ABSS of social dilemmas presented in this subsection are built on the foundations from social dilemma research presented in section 2.1. Therefore they naturally conform with requirements A to C. In addition, all approaches utilise the potential of ABSS (see section 2.2.2). Thus, they are also in line with the demand to include spatial and temporal dynamics (requirement D).

On one hand, the modelling concepts presented in this subsection are well grounded in theory. On the other hand, the involved psychological conceptions (see section 2.3) offer descriptive insights into the drivers of individual decision-making on the micro-level and may well be linked to different sources of empirical founding. In conclusion, these ABSS approaches in the domain of social dilemmas cover a middle range of abstraction in between highly abstract thin simulations and highly specific and descriptive thick simulations.

2.2.4 Synthesis IV: Requirements E and F of research method

This subsection summarises the main conclusions from the review of existing ABSS work on social dilemmas by formulating two additional methodical requirements.

Requirement E: Medium level of abstraction

The gap between abstract thin simulations and descriptive thick simulation is filled by theoretically sound simulations on a medium level of abstraction. These middle range models (Gilbert, 2008, p. 42) capture the observed individual and structural characteristics of a problem domain such that the model remains applicable to similarly structured cases. Simulations with middle range models reproduce dynamics observed in reality and expected future dynamics in a qualitative way whereas quantitative validity is no core requirement. Middle-range models are in principal sound in their theoretical foundations and enable the integration of a "blend" of methods for empirical foundation.

Requirement F: Psychological soundness

People's decision-making in a dilemma situation is not simply cooperative or defective. In contrast, humans show a spectrum of different behaviours for various individual reasons that in total emerge to be rather cooperative or rather defective in the dilemma context. Therefore, the representation of such behaviours in an ABSS has to be guided by relevant psychological theories (Jager & Mosler, 2007). Albeit the fact that numerous theories may be relevant there exists a core set of aspects that are to be included in psychologically sound agents for social simulation (Briegel et al., 2012; Elbers, Ernst, Krebs, Holzhauer, & Klemm, 2009; Ernst, 1994; Jager & Mosler, 2007; Krebs et al., 2011; Nerb et al., 1997; Schwarz & Ernst, 2009): Goals guiding individual behaviours, heterogeneous goal preferences, social influence, social comparison, and imitation, learning and adaptation of behaviour, decision-making by cognitively expensive deliberation like planning, routine behaviours like habits and experimentation/exploration.

Requirement E sets an ABSS focus and lays down the characteristics of generic, middle-range ABSS of social dilemmas. Requirement F takes the perspective of psychological research on individual decision-making in ABSS. The following section provides a focused introduction to the concepts relevant to psychologically sound ABSS.

2.3 Psychology of decision-making

We already stressed the psychological perspective on decision-making in public good dilemmas in some of the preceding sections. For example much of the theoretical and empirical work presented in section 2.1 follows a classical psychological approach. Furthermore, it was shown in section 2.2.3 that the methodical approach of ABSS to a substantial portion demands the inclusion of psychological theory (see requirement F).

It is the purpose of this section to provide a sufficiently complete overview of basic psychological concepts of human decision-making. In doing so, we will somehow pragmatically filter the relevant research by accounting for the methodical requirements identified in the previous sections.

From the perspective of ABSS development two model components require the inclusion of psychological theory: one that describes the intra-psychological processes of individuals with reference to their contribution behaviour in public good dilemmas, and the other reflecting the individual's embeddedness in an environment of social exchange with others.

The first subsection covers the intra-individual perspective. Two classical and complementary approaches to predicting intentions and behaviours are presented. We start in section 2.3.1.1 by introducing and discussing the neoclassical model of utility-based decision-making. While the utility approach is very general in nature, section 2.3.1.2 introduces a genuine psychological theory that focuses very specifically on the class of altruistic behaviours which clearly play a key role in the domain of public good provision.

In a second subsection, acknowledging the importance of social embeddedness of individual decision-making, we focus on social influence as the core mechanism of the dynamics implied by social structure. Here, we take the perspective of social psychology.

The third subsection closes the overview by presenting the Theory of Planned Behaviour as a theory framework that provides an empirically founded and psychologically sound calculus to integrate personal attitudes, norms and social influences in deliberative decision-making.

Finally, we discuss the obtained insights and motivate why the Theory of Planned Behaviour is a psychological framework that fits the methodical demands derived in the preceding sections.

2.3.1 The Individual perspective: Subjective determinants of decision-making

The importance of the subjective and individual perspective on decision-making in social dilemmas is formulated in requirement A. This section introduces some basic psychological concepts and theories used to describe, understand and predict human decision-making. Here, we focus especially on aspects of decision-making that are internal to the individual. Social phenomena involving groups of decision-makers are covered in section 2.3.2.

The key questions of psychological research on individual decision-making are: (a) how do internal dispositions of humans relate to their observable behaviour? And (b) what are the processes that modify the internal dispositions in response to external stimuli? Research on the first topic aims on developing theories that explain the relationship between persons' subjectively reported internal dispositions like perceptions, attitudes, personal norms, motivations, efficacy beliefs and behavioural intentions, and the behaviour they objectively perform. The second research topic focusses on the learning processes that "construct" the internal dispositions, and that lead to behaviour.

We start by introducing and discussing the idea of utility-based decision-making which originates from economics but is also applied in psychology (Fishbein & Ajzen, 1975). The underlying assumption is that behaviour in general can be explained by subjective utility expectations of the individual. Such a numerical, calculus-based notion of decision-making becomes especially relevant when it comes to ABSS implementation. This is followed by the presentation and discussion of the Norm Activation Model of prosocial behaviour (NAM; Schwartz, 1977) which explains altruistic behaviour by personal norms of individuals. In contrast to the utility approaches Schwartz's theory offers a cognitive and sequential model of individual decision-making that covers the entire process from norm-activation to action.

2.3.1.1 Expected utility models

The Subjective Expected Utility model (SEU; Edwards, 1954) is one of the most prominent early decision models of behavioural decision theory. In proposing the SEU model Edwards questioned the prevalent rational actor paradigm of his time that assumed that individuals possess complete and objective knowledge of a decision context (cf. section 2.1.1.1). He stresses the influence of risk and uncertainty, and introduced notions of likelihood and expectancy in the decision model. The theory states that if a person makes a behavioural

choice, he will reason about the subjective utilities associated with each of his behavioural alternatives and select the option he expects to yield the most favourable outcome.
For a given behavioural option b_i the subjective expected utility SEU_i is defined as follows:

$$SEU_i = \sum_{k=0}^{n} p_k u_k$$

In the formula p_k is the subjective probability that the behavioural alternative b_k will yield outcome o_k, whereas u_k is the subjective value of o_k, and n is the number of possible outcomes. Accordingly, p_k may be seen as the strength of an individual's belief that behaviour b_i is associated with outcome o_k. In the SEU model, if an individual has m alternatives of behaviour, the process of individual decision-making can be modelled by calculating SEU_i for i=1…m and selecting the behaviour with the highest calculated subjective expected utility value.
The SEU approach accounts for an decision-maker's subjectivity in two ways: The belief strengths reflect subjective knowledge on the causal relationship between a behaviour and its consequences, and the evaluation of the possible consequences reflects the subjective preference of an individual for a specific outcome. Still, the underlying assumption remains that individuals have the respective "chunks" of information always at their disposal and that they process their knowledge completely and perfectly when decisions have to be made.
Basically, the SEU model assumes that each option of behaviour available to a decision-maker is associated with exactly one outcome. In the context of economic decision-making this is perfectly useful because consequences are understood to be quantifiable comprehensively with respect to their mere monetary outcome. However, non-economic decisions usually involve multiple consequences (Keeney & Raiffa, 1993), i.e. for a decision-maker there may be various beliefs linking a given behaviour to a number of different outcomes. These circumstances are reflected in the generalised version of SEU model which is known as the multi-attribute utility (MAU) model.
When it comes to outcome evaluation the key assumption of MAU is that values can be expressed in common units, whatever their underlying dimensions. Therefore, the MAU of a behaviour may be calculated straight forward by summing across multi-faceted outcomes.

The subjective evaluation of an outcome by an individual is sometimes called the individual's preference for the outcome and the set of preferences for all possible outcomes is called the individual's preference set.

Like SEU, MAU assumes an ideal decision maker who is well informed about all possible outcomes and who computes perfectly. In contrast to this presumption it was e.g. shown that humans show biases in their judgments (Kahneman & Tversky, 1984) that can lead to failure of the classical model. In addition, Gigerenzer, Todd, and Abc Research Group (1999) have shown that decision-making often follows simple heuristics, i.e. in contrast to the assumptions of SEU and MAU, decision-making sometimes occurs in a very simplified manner evaluating only one outcome dimension or only a small subset of decision alternatives.

Applied to the case of public good provision, subjective utility would relate individual investments in the public good to obtained benefits. Furthermore, other individual factors that may be expressed in economic terms (e.g. social value orientations, inequity aversion, or reciprocity; see requirement A) can be incorporated in a utility function.

However, the utility model seems to fail in representing the affective dimension of altruism: People sometimes derive utility from the mere act of giving in a public good dilemma - irrespective of the quantity of the good that is provided and independent of the fact that others will be better off. In economics, this "impure altruism" (Andreoni, 1990) is discussed under the heading of "a warm glow of giving" or "purchase of moral satisfaction" (see Andreoni, 1990; Kahneman & Knetsch, 1992). In addition, Kahneman & Knetsch (1992) show that moral satisfaction may vary with the good: some goods give more satisfaction than others. The following section introduces a psychological action model that explicitly covers the cognitive processes underlying such moral-driven behaviour.

2.3.1.2 Norm activation model

The Norm Activation Model (NAM; Schwartz, 1977) focuses on the explanation of prosocial, altruistic behaviours. For this specific class of behaviours, the NAM postulates that decision-making is governed by feelings of moral obligation to act in a way that conforms to one's personal norms. Personal norms are understood to be highly internalised in nature and refer to an individual's subjective conviction that behaving in a certain way is right or wrong in a given context.

In the NAM the activation of a specific personal norm is conditional upon a situational problem perception by the individual, i.e. the anticipation of negative consequences if no action is taken. If the perceived problem context triggers a personal norm, the individual will engage in a cost-benefit analysis that considers the material or psychological cost of conforming to the personal norm. Depending on this subjective evaluation a respective behavioural intention may be formed or, if the expected cost of performing the behaviour is too high, the activated norm may in turn be neutralised, e.g. due to a lack of personal ability or responsibility.

The NAM was successfully applied in predicting prosocial intentions in numerous empirical contexts like donating blood, helping in emergency situations, and also proenvironmental behaviour (see summary in Groot & Steg, 2009, p. 426).

The NAM covers the case of prosocial behaviours which clearly play a key role in the case of public good provision. Furthermore, on a conceptual level, the NAM deals with requirements A to D as formulated in section 2.1.4: According to the theory, prior to norm activation, the individual has to recognise a problem situation which clearly represents a way of perceiving an individual's embeddedness in a dynamic spatial and social context as demanded by requirement B, C, and D. In addition, norm activation is based on a subjective set of personal norms specific to an individual, which is in line with requirement A. Likewise, the final evaluation of the efficacy of norm-conforming behaviour may be subjective to the individual. Personal norms are at the heart of the NAM as they are seen as direct, unmediated causal determinants of prosocial behaviours. However, the theory does not make statements on the adaptation and emergence of personal norms. One might suspect that Schwartz understands personal norms as internalisations of previously perceived social norms, and that personal norms may therefore be seen as a result of social learning (see section 2.3.2). Yet, the NAM does not cover the mechanisms underlying such dynamics. Likewise, the criteria allowing the individual to assess the personal consequences of a norm-conforming behaviour are not specified in the theory. In summary, the NAM is little compatible with the typical capabilities of ABSS, in particular concerning individual-level and collective dynamics.

2.3.2 The social perspective: Implications of individual embeddedness

2.3.2.1 Social influence and social conformity

Requirement C stresses the importance of the social structure in which individuals act in a social dilemma situation. Research on social structure originates from sociology. While sociology sees social structure as a macro-level property of human societies, the effects of social structure on individuals are the subject of social psychology (Aronson, Wilson, & Akert, 2005; Smith & Mackie, 2007). A core conception of social psychology is that social structure impacts individuals through social influence, which is defined as “The effect that the words, actions, or mere presence of other people have on our thoughts, feelings, attitudes, or behaviour” (Aronson et al., 2005, p. 5).

The study of social influence lies at the heart of social psychology: Topics such as conformity, obedience, and persuasion are obviously and directly grounded in considerations about how one’s thoughts and actions are influenced by other people. Likewise, other research areas of social psychology like e.g. social relationship formation and maintenance, attitude formation, social learning, group think, power relations, or in-group-out-group relations critically involve social influence.

Early evidence on the effect of social influence is documented by Asch (1955). His experiment showed that even if people know the right answer to a certain question, if they observe their fellow test persons in the lab room to select wrong answers, they also tend to answer wrongly. Asch concludes that test persons in his experiment deliberately chose wrong answers in order to achieve conformity, increase acceptance, and avoid disapproval by other group members.

Clearly, such experiments demonstrate that what people privately think or intend to do not necessarily matches their publicly shown behaviour or expressed opinions. Apparently, in the explanation of this gap, social influence plays a key role. Furthermore, experiments appear to illustrate two different “flavours” of social influence.

Following Asch’s research Deutsch & Gerard (1955) introduced the distinction between normative social influence and informational social influence. Informational influence is an influence to accept information from others as evidence about reality. Informational influence becomes important in situations when people are uncertain, e.g. because they encounter new situations where available knowledge is unusable or ambiguous, or because there is social disagreement about a suitable way to act. Normative influence is an influence to conform to the positive expectations of others. The assumption is that people adjust their behaviour in order to achieve social approval within their group.

These two definitions are well motivated, straight forward and widely used. Furthermore, the concepts have some notable implications on the attitude-behaviour relationship: For example "…it is possible to conform behaviorally with the expectations of others and say things which one disbelieves but which agree with the beliefs of others. Also, it is possible that one will accept an opponent's beliefs as evidence about reality even though one has no motivation to agree with him per se." (Deutsch & Gerard, 1955, p. 629)

In the more current literature (e.g. Aronson et al., 2005; Smith & Mackie, 2007), authors refer to the concept of conformity as the most prevailing mechanism of social influence involving a change in attitude or behaviour in order to fit in with a group. Again, research in conformity tends to distinguish between informational conformity and normative conformity. The two varieties of conformity are understood as two psychological needs that make people conform to the expectations of others: The need to be "right" (informational social influence) and the need to be "liked" (normative social influence).

The informational–normative distinction provides only broad categories that are not necessarily disjunctive. The two psychological needs can usefully be broken down to a set of distinct goals that guide individuals in conforming to others' opinions (Cialdini & Goldstein, 2004). One such goal is to achieve an accurate understanding of the world (corresponding to informational influence); another goal is to successfully maintain adequate social relationships (corresponding to normative influence). Cialdini & Goldstein (2004) propose a third goal that reflects the need to maintain a positive self-image for oneself and for others.

2.3.2.2 Dynamics and social networks

A majority of the classical contributions from social psychology to the investigation of conformity phenomena assume static social influence environments. This tradition is much owed to the experimental approach and neglects the inherently dynamic nature of the underlying individual-level processes: Behaviours within groups change dynamically over time in response to individual conformity needs. Likewise, attitudes and communicated opinions shift as a result of individual-level cognitive processes responding to the social dynamics surrounding the individual.

Social Impact Theory (SIT; Latané, 1981) reflects the understanding that, much like physical force fields, social influences can be seen as social forces operating on the social structure individuals are part of. In principle, an individual may perceive such social forces as being informational, normative, or both. According to SIT, the social impact on an individual increases with (a) the strength of the sources of influence that the individual is target of, (b) their immediacy, and (c) the number of sources.

The theory was further extended to allow for dynamical investigations by computer simulations (DSIT; Dynamic Social Impact Theory; Latané, 1996; Nowak, Szamrej, & Latané, 1990). The theory's numerical tractability enabled explorative simulations that predicted various forms of macro-level patterns emerging from micro-level interactions like the clustering of attitudes in social space, or persisting diversity of attitudes, i.e. a general absence of global convergence.

While SIT defines social "immediacy" as spatial closeness on a grid topology, the Structural Theory of Social Influence (STS; Friedkin, 1998) generalises this view by allowing arbitrary patterns of social closeness. In short, the theory represents relations of social influence between n individuals as an nxn matrix where matrix cell (i, j) holds a numerical value representing the strength of influence individual i has on individual j. Such structural patterns are most usefully conceptualised in the social networks framework (Wasserman & Faust, 2009). Social networks are understood as a network topology providing the infrastructure for social exchange where network nodes are individuals and social influence is exerted or received through network links.

In terms of social networks, traditional social psychology mostly takes the perspective that individuals in a (laboratory) group are embedded in a fully connected network in which in principle all individuals can directly influence each other.

More realistically, SIT relaxes this view by including the immediacy of social influences. From the network perspective, DSIT considers lattice networks, in which each individual is influenced by a few immediate neighbours. Here, spatial closeness on a cellular automaton is used to represent social closeness relations. However, the underlying Euclidian distance relations restrict the richness and complexity of possible social relations.

The contribution of Friedkin's STS is the introduction of heterogeneous networks allowing for arbitrary patterns of connectedness and for directed links. The conception links research on social influence to social network research and its numerical methods of analysis (Wasserman & Faust, 2009). Furthermore, it enables the representation of commonly observed network structures like e.g. small-world networks (Watts & Strogatz, 1998) or scale-free networks (Barabási, 2002).

2.3.3 Integrating the subjective and the social: The Theory of Planned Behaviour

A psychological theory that integrates the individual perspective of decision-making (see requirement A) and the implications arising from the social embeddedness of decision-making (see requirement C) is the Theory of Planned Behaviour (TPB; Ajzen, 1991, Ajzen, 1985). The TPB deals with the explanation and prediction of individual deliberative behaviour.

The TPB assumes that the intention to behave in a certain way is the only direct psychological determinant of overt behaviour and that an intention is formed by summarising all the pros and cons when a person deliberately reasons whether he should perform a behavioural option or not. The strength of an intention indicates a person's willingness to devote physical and psychological effort in performing the chosen behaviour.

According to the TPB, intention is determined by a subjective attitude towards the behavioural option that results from an individual's evaluation, and by a subjective norm that reflects perceived social pressure towards or against the behaviour. As Ajzen (1985), p. 12 puts it: "…people intend to perform a behaviour when they evaluate it positively and when they believe that important others think they should perform it." In order to combine the two dimensions and to predict a resulting intention the theory represents the respective influence strengths of the attitudinal and the normative component. The theory is backed by many case studies in which it was confirmed that attitudes and subjective norms highly correlate with intentions and subsequently with behaviour in the case of deliberate behaviour (Ajzen, 1991; Ajzen & Fishbein, 2005). However, intentions do not necessarily result in behaviours. Even if attitude and subjective norm yield a strong intention to perform a behaviour, conditions external to the decision-maker may prevent the behaviour from being put into action. To cover this aspect, Ajzen introduced the concept of "perceived behavioural control". In cases where behavioural options are under full control of an individual TPB predicts that intentions translate directly into behaviours. In all other cases TPB takes into account the perceived and the actual control an actor has over an intended behaviour.

Finally, Ajzen & Fishbein (2005) stress that the involved beliefs people hold about the performance of their behavioural options are influenced by a multitude of background factors and thus account for substantial variance within a population. Figure 4 illustrates the formation of intentions, behaviours, and their respective antecedents.

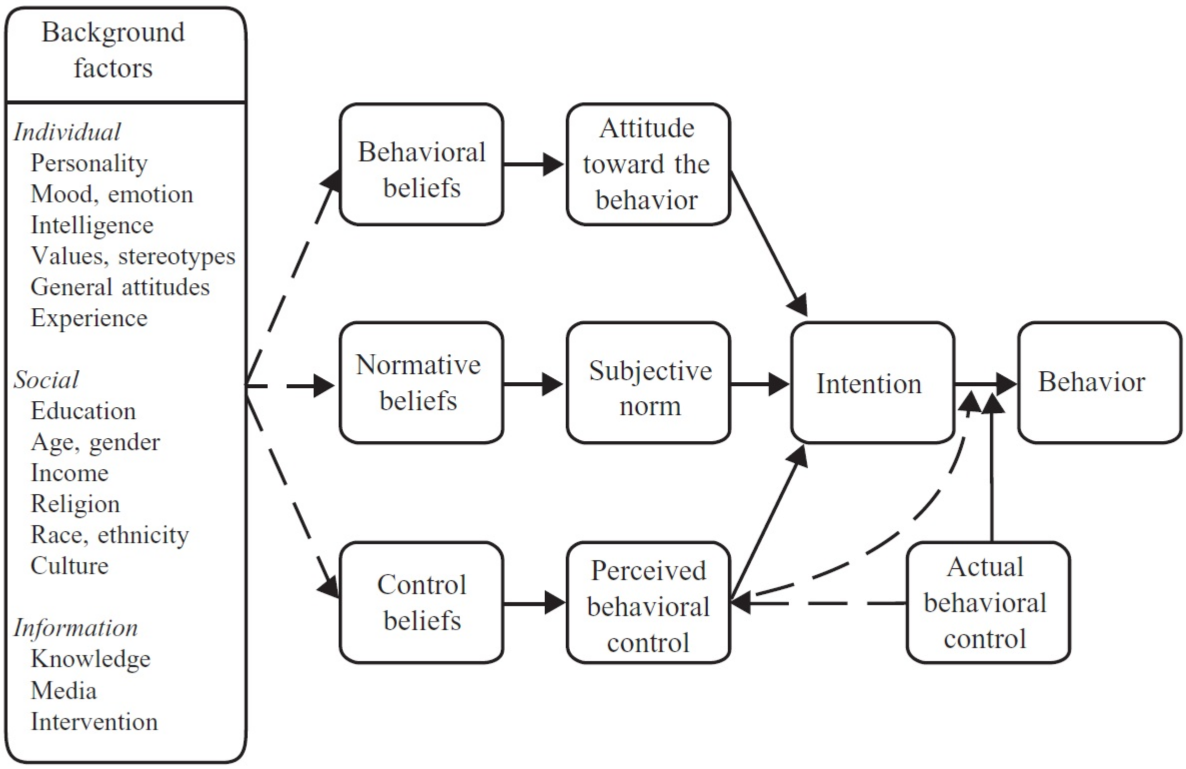

Figure 4. The Theory of Planned Behaviour. Source: Ajzen & Fishbein (2005), p. 194

The TPB is strongly grounded in the calculus introduced in section 2.3.1.1. The attitude towards a behaviour reflects the behavioural beliefs of a person about the outcomes of the behaviour and the respective evaluations of the consequences. Likewise, the subjective norm depends on normative beliefs about the acceptance of the behaviour by important reference persons. Similarly, perceived behavioural control is determined by specific control beliefs and their expected influence on preventing or promoting the performance of a behavioural option.

2.3.4 Synthesis V: The potential of the Theory of Planned Behaviour in the domain of social dilemmas

When it comes to modelling human actors, some of the fundamental concepts involved in designing an ABSS have their foundations in the research field of psychology. Well established psychological groundwork exists on subjective attitudes, behaviour, and the adaptation of behaviour. Furthermore, social psychology offers a rich toolbox of methods, concepts, and theories covering inter-individual processes like social influence or collective phenomena like emergence. Therefore, in line with the scholars cited in section 2.2.3.4 and in compliance with requirement F, we argue that ABSS has to include relevant and appropriate psychological concepts and theory. This section aimed at overviewing some of the involved concepts of the psychology of human decision-making.

We concluded by proposing the TPB as a suitable psychological framework that integrates both subjective attitudes towards behaviours and social influences into individual decision-making. The TPB is unique in its empirical founding and in its numerical tractability. The involved calculus is based on MAU on the level of individual actors which offers a lean and straight forward way of implementation in ABSS exercises.

Regarding the problem domain of public good dilemmas the TPB complies with requirements A and C because it explicitly represents the contrast between the individual perspective and the social factors of decision-making. The requirement B of spatial embeddedness is included in the TPB in the form of environmental background factors and in belief formation based on perceptions of the environment, especially concerning behavioural control beliefs. In principle, the TPB is a static theory. However, as a decision core in an ABSS the theory is open to account for the temporal and collective dynamics of decision-making because the feedback of an agent’s behaviour to other constructs of the theory is clearly specified. While past behaviours directly impact subsequent processes of individual belief updating, the feedback of an agent’s subjective behaviour on the social norm perceived by other agent’s is a crucial driver of collective behavioural dynamics.

Therefore, in an ABSS exercise the TPB can account for requirement D. Finally, the TPB is not restricted to specific application domains. Therefore, the theory can serve as a psychological framework for middle-range ABSS as demanded by requirement E.

The TPB does not claim to cover all "modes" of human decision-making. The theory explicitly focuses on reflected and deliberate behaviour. The TPB does not consider repetitive, habitual behaviour. Similarly, other less reflected forms of decision-making like heuristics or even irrational behaviour are not the scope of the TPB. Still, it is adequate to regard deliberation as the core driver of the decision dynamics in an ABSS. For instance habits can plausibly be understood as routines emerging from prior reflected decision-making (Aarts & Dijksterhuis, 2000).

Another point has to be made on the implications arising from the "mental calculations" at the heart of TPB. In section 2.3.1 we argued that the involved notions of subjective utility have some drawbacks in their compatibility with the paradigm of bounded rationality. However, this argument is substantially weakened when the TPB is applied in an ABSS context that naturally accounts for various forms of subjective and limited information processing on the micro-level of agents (see section 2.2.2).

2.4 Concluding summary

In the introduction of this chapter we promised to provide the perspectives of different scientific disciplines on the problem domain of decision-making in public good dilemmas.

In doing so, we started in section 2.1 by reviewing the classical theoretical and empirical approaches of social dilemma research. This branch of research has a long ranging tradition reaching from the historical game-theoretic conceptions to empirical approaches like human subject lab experiments or field study analysis. On the theoretical side, the contribution to this dissertation is the definitional framing of public good dilemmas and resource dilemmas as the two fundamental representatives of social dilemmas. On the empirical side, we reviewed existing work on the mystery that lies at the core of social dilemma research: Why do people sometimes behave in ways that fundamentally contradict their objectively existing selfish interests? In striving to obtain a coherent picture of the numerous existing explanation approaches, in synthesis I, we proposed an abstract systems overview that serves as a map of the locations where the various factors that influence cooperation take effect. We concluded with synthesis II that extracts the core contributions of this research tradition and formulates four mandatory demands of the research method of this dissertation.

The methodical approach of this dissertation is agent-based simulation. In section 2.2 we introduced the method and in synthesis III we motivated its general appropriateness for the investigation of public good dilemmas by relating the method to the requirements derived before. Furthermore, we narrowed down the multitude of candidate styles of ABSS modelling. In synthesis IV we formulated the distinctive features of ABSS that are well grounded in psychological theory while still remaining sufficiently generic.

Section 2.3 completes the picture by introducing concepts of psychology of decision-making and social psychology that are crucial to ABSS and by presenting the Theory of Planned Behaviour. Synthesis V comprehensively motivates why the TPB can appropriately cover all methodical demands formulated in the preceding sections and why it is therefore the suitable psychological theory framework for the modelling approach of the dissertation.

The main messages of this chapter are put down in the five synthesis sections. We will forward these insights to the following chapters as a structured set of criteria for aligning and validating the research method of this dissertation.

3 A psychologically sound middle-range agent-based social simulation of collective decision-making in public good dilemmas

This chapter reports on the main theoretical and methodical contributions of the dissertation. Based on the insights obtained in chapter 2 we propose a generic model of individual decision-making in public good dilemmas and its embedding in an ABSS. Our starting-point is the systems overview given in synthesis I (see section 2.1.3) which provides a conceptual outline of the embeddedness of individual decision-making for the case of public good dilemmas.

Section 3.1 introduces and motivates the theoretical model of preference-guided action selection in public good dilemmas that underlies the decision core of the ABSS. In terms of the systems overview of synthesis I we provide a specification of the actor perspective on decision-making shown in Figure 3.

While Section 3.1 proposes a psychologically sound theory of decision-making in public good dilemmas, Section 3.2 takes a methodical perspective and reports on the integration of the theory in an ABSS exercise. The goal is to set-up a middle-range ABSS which represents the most important properties and dynamics of the problem domain while remaining sufficiently abstract to allow for a systematic analysis of the collective behavioural dynamics and macro-level patterns implied by the theory.

The results of the dynamical analysis of the abstract ABSS are reported in section 3.3. Here, the focus is twofold on validation of the decision core and on the identification of suitable parameter ranges for case-specific parameterisation of the model.

Section 3.4 concludes.

3.1 Conceptual model of individual decision-making

This section proceeds as follows: In subsection 3.1.1 we present the theoretical model which is the grounding of the decision core of the ABSS. Then, subsection 3.1.2 embeds the theoretical model into the problem domain by linking it to the requirements derived in the synthesis sections of chapter 2.

3.1.1 Model description

This section defines the HAPPenInGS model (**H**eterogeneous **A**gents **P**roviding **P**ubl**i**c **G**ood**s**) of preference-guided action selection of individuals in public good dilemmas. HAPPenInGS is specific in being grounded in the theoretic concepts and empirical results on social dilemmas and public goods, as well as in psychological theory of decision-making. However, the model is retained as generic as possible and therefore independent of a specific case context.

Figure 5 illustrates the structural components of HAPPenInGS and their interaction. Arrows show the variables with their names and illustrate the sequence of their processing in the numbered blocks.

Block 1 represents the deduction of an investment decision based on four influencing factors that are partly results of pre-processing in other blocks:

- The attitude towards an investment option in terms of the individual advantage the agent associates with the respective behaviour (*Expected benefit of public good*),
- the expected conformity of an investment option with existing social norms, i.e. the subjective norm in terms of the perceived social pressure to perform or not to perform the behaviour (*Expected behavioural conformity*),
- the expected conformity of an investment option with individual preferences regarding the distribution of investments among members of the providing group (*Expected compliance with distributional preferences*), and
- the perceived behavioural control regarding an investment option reflecting the availability of required opportunities and resources to perform the actual behaviour (*Available investment behaviours*).

While the latter factor is seen as a more or less persistent property of an individual the first three factors are dynamically adjusted based on perceptions. The processing of the perceptions is done in blocks 2 to 5.

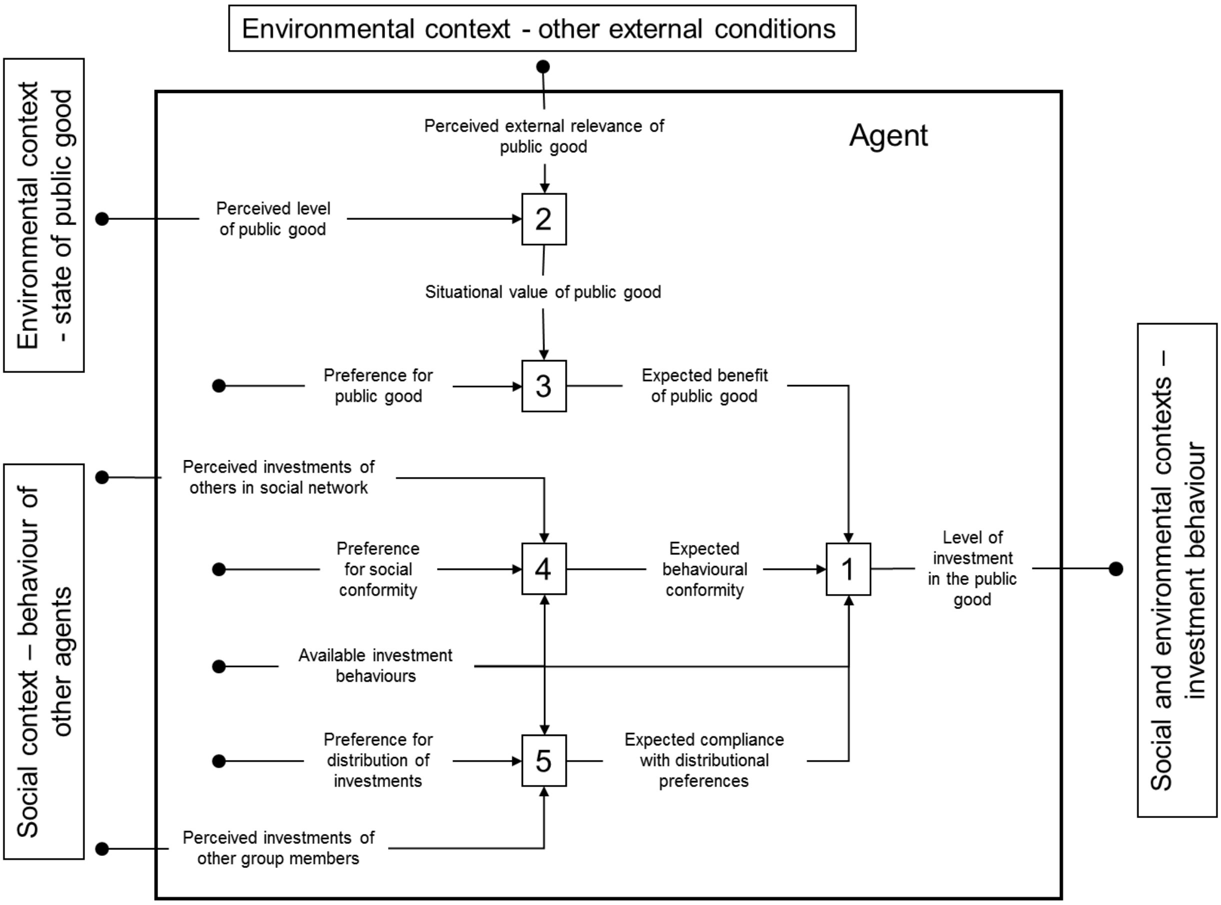

Figure 5. Overview of the HAPPenInGS model. Arrows show the variables with their names and illustrate the sequence of their processing in the numbered blocks. See text for further explanations.

Block 2 covers the situational dimension of the public good: Individuals perceive the objective quality or quantity of the public good provided by their respective group (*Perceived level of the public good*) in relation to the necessity or urgency of the public good in a given external context (*Perceived external relevance of the public good*). The result of block 2 is a quantification of the salience of the public good in the respective context (*Situational value of public good*).

Block 3 relates the salience of the public good to the subjective preferences of an individual regarding the public good (*Preference for public good*). In the sense of the TPB this preference reflects the strength of influence that the perceived level of the public good has on the individual investment decision, e.g. high preference values in conjunction with low levels of the public good increase utility expectations for high investments. The result of the block is a measure for the expected conformity of an investment option with the modelled attitude of an agent regarding the public good (*Expected benefit of public good*).

Block 4 covers the formation of a subjective norm towards a behaviour. Individuals assess investment options with respect to behaviours observed in their social network (*Perceived investments of others in social network*). The focus is on the normative component of interpersonal social influences that entails the tendency to conform to the behavioural expectations of others (see section 2.3.2). The individual influence weight of the subjective norm is represented as a subjective preference for socially conform behaviour (*Preference for social conformity*). The result of the block is a measure for the expected conformity of an investment option with prevailing behaviours in the social network (*Expected behavioural conformity*).

Likewise, block 5 processes behaviours observable in an agent's social context. However, in contrast to block 4 the focus is on the relation of the decision making agent's investment option to the behaviours within his providing agent group. Here, we represent individual preferences regarding the distribution of investments within the providing group of the focal agent (*Preference for distribution of investments*). These preferences allow e.g. representing social orientations (see section 2.1.2.1). Egoistic or pro-self-preferences would e.g. favour investment options that are lower than investments chosen by other group members. Again, the output of the block is an expectation about the conformity of an investment option with the individual distributional preferences (*Expected compliance with distributional preferences*).

3.1.2 Compatibility of HAPPenInGS with requirements A to F

Clearly, HAPPenInGS was formulated in the light of the multi-disciplinary scientific context laid out in chapter 2. This section is to substantiate this conceptual embeddedness of HAPPenInGS by making reference to the requirements derived in chapter 2.

Requirement A stresses the role of subjectivity of an individual in a public good dilemma. In HAPPenInGS such actor heterogeneity is represented as subjective preferences that guide individual decision-making. The three preference dimensions covered in HAPPenInGS were purposefully chosen to enable the weighting between an attitudinal dimension (*Preference for public good*), a social-normative dimension (*Preference for social conformity*), and a dimension representing social value orientations (*Preference for distribution of investments*). While the latter preference covers an essential individual factor influencing cooperation in social dilemmas (see section 2.1.2.1), the former two preferences represent core elements of the TPB (see comments on requirement F below).

In HAPPenInGS, **requirement B** on spatial embeddedness is represented by the environmental context (see also Figure 2). The embedding provides the decision-maker with local perceptions of the present state of the public good and of other (case-specific) non-social external factors relevant to the decision process. Furthermore, behaviours that are put into action change the state of the environment. In addition, individuals are embedded in a non-social temporally and spatially dynamic context as demanded by **requirement D**. This embedding allows perceiving the consequences of individual and collective behaviours (*Level of the public good*) and the generally varying temporal/spatial salience of the public good (*External relevance of the public good*).

Likewise, **requirement C** on the social embedding of decision-making is met by HAPPenInGS. An individual's perception of its social context is represented by allowing individuals to relate their behaviour to the behaviour of network peers in general (*Perceived investments of others in social network*) or to the behaviours of others in their respective providing group (*Perceived investment of other group members*) in specific. In general, social exchange mechanisms other than mere observation of behaviours may become relevant, e.g. in the form of messages of social approval or disapproval sent and perceived through social network ties.

In line with **requirement F**, the model is psychologically sound because the core formalisation of decision-making in HAPPenInGS is the TPB with the extension of distributional preferences. Perceived behavioural control in the sense of the TPB is represented as a fixed set of behavioural options that sets limits to an individual's repertoire of action. In HAPPenInGS the formation of an intention is bounded to the scope of these *Available investment options.* For our purposes, we assume that intentions are always put into action and translate directly to behaviour. Individual background factors are expressed by assigning subjective preference sets and by an individual's embedding in its environments.

In principle, the operational sequence of the NAM may be reproduced in HAPPenInGS: The perception of a context that triggers a personal norm can be seen as the perception of external conditions which is evaluated to a high situational value of the public good in block 2. This evaluation would increase the expected benefit from the public good and favour high investment behaviour (as a personal norm). This expectancy might then dominate the expected behavioural conformity and compliance with distributional preferences in block 1, resulting in norm activation. Otherwise, the personal norm is deactivated.

Finally, the methodical approach of ABSS that will be outlined in section 3.2 in principle makes a significant account for requirements A to E as was detailed out in synthesis III (see section 2.2.2).

3.2 Embedding the individual: Abstract agent-based social simulation setup (HAPPenInGS-A)

This section takes a methodical perspective and outlines an abstract ABSS setup based on HAPPenInGS as the theoretical founding of agent decision-making (HAPPenInGS-A). The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006; Grimm et al., 2010).

3.2.1 Purpose

With HAPPenInGS-A, we aim to demonstrate the effect of micro-level individual preferences on the level of a collectively provided public good. The goal is to assess the validity and the implications of HAPPenInGS and to identify suitable ranges for the preference parameters for case-specific parameterisation of the model.

3.2.2 Entities, state variables, and scales

3.2.2.1 Environments

In line with the systems overview (see Figure 2) the external situation characteristics in HAPPenInGS-A are composed of two distinct entities, namely the environmental and the social contexts.

The environmental context has a grid topology. Each of the grid cells is characterised by a real number c representing the level of the public good provided by the agents located on the respective patch of the grid. The number of agents located on a patch is the same for all patches.

The social context has a network topology. We initialise a directed social network where a network link from agent A to agent B means that B is influenced by A. In the model, the investment behaviour of A is perceivable by B and contributes to B's evaluation of its social conformity goal along with the behaviours of all other agents having outgoing social network links to B. The social network is set up during initialisation and remains fixed throughout the simulation.

3.2.2.2 Agents

Agents have a fixed position in the environmental context given by the patch they are located on. An agent's embedding in the social network is represented as a list of other agents which are linked to it by ties of the network.

Agents have four persistent state variables represented as real numbers from the interval [0.0; 1.0] which define their preferences according to HAPPenInGS: While the preference for the public good and the preference for social conformity are each represented by one state variable, the preference for distribution of investments is represented by two state variables quantifying a desired weighting between own contribution and contributions of other group members.

Finally, agents have temporally varying state variables storing the planned investment for the next time step, its expected utility, and the last executed investment.

3.2.3 Process overview and scheduling

The basic processes of the model and their respective triggering are documented in the pseudo code shown below. The pseudo code describes the simulation cycle after model initialisation (see section 3.2.5). Each simulation time step starts by calculating the level of the public good provided on each of the patches of the environmental context. To do so, for each of the agent groups the local level of the public good is calculated based on the agents' investment decisions in the previous time step. Next, each agent perceives various attributes of its social and environmental contexts. Subsequently, each agent selects a mode of decision-making (see sub model section 3.2.7.2 for details). With a probability of 99% an agent decides deliberatively about its investment behaviour in the next time step based on its perceptions, on its preferences and on its internal state (memorised experiences) following the HAPPenInGS theory. With a low probability of 1% an agent "explores" by randomly selecting the investment behaviour that will be put into action in the following time step.

```
for each timestep {
  for each patch {
    calculateLevelOfPublicGood
  }
  for each agent {
    perceiveLevelOfPublicGoodOnPatch
```

```
      perceiveBehaviourOfOtherGroupMembers
      perceiveBehaviourOfNetworkPeers
      with probability 99% {
         decideByDeliberation
      }
      else {
        decideByExploration
      }
    }
  }
```

3.2.4 Design Concepts

This section summarises the main design concepts of HAPPenInGS-A. The concepts according to the ODD protocol are stated in italics.

The *basic principle* addressed by HAPPenInGS-A is collective action for the provision of public goods. When do heterogeneous groups of individuals manage to provide a collectively desired good and when do they fail? The public good is assumed to emerge from the individual contributions made by members of the local agent groups on spatial extents of the environment (*Emergence*).

The behavioural target variable of an agent is the individual investment in the next time step of the model. Possible interference with the generally multi-facetted decision-making in contexts other than the public good provision is not considered. Deliberative decision-making is modelled by an implementation of HAPPenInGS: Investment options are evaluated with respect to the subjective preferences of an agent (*Objectives*) yielding an expectation of the subjective utility that is associated with executing the behaviour (*Prediction*). The selection of a behaviour is based on the comparison of expected utilities associated with the behavioural options at an agent's disposal (*Adaptation*). With a fixed low probability an agent skips deliberative decision-making and "explores" by selecting a behavioural option at random. *Learning* is not considered in HAPPenInGS-A.

Agents can perceive the behaviour of other agents in their group and the behaviour of neighbouring agents in their social network (*Sensing*). Furthermore, agents perceive the level of the public good provided by their group (*Sensing*). These perceptions are used in the utility calculation according to HAPPenInGS. Apart from these perceptions agents do not interact with each other (*Interaction*).

Stochastic processes are involved during the initialisation when assigning agents to patches and when setting up the social network (*Stochasticity*). Furthermore, decision-making has pseudo-random components: During deliberation, behavioural options are selected with a probability reflecting their expected utility. During exploration a behavioural option is selected at random where each behaviour has the same probability of being selected (*Stochasticity*).

Agent *collectives* are implied by the position of individual agents in the environmental context. Agents located on the same patch belong to an agent group that collectively provides a local public good on the respective patch.

The main outputs of the model are based on observed investments behaviours of individual agents and on the level of the public goods provided by the agent groups. Further performance indicators are introduced when discussing the simulation results in section 3.3 (*Observation*).

3.2.5 Initialisation

The environmental context consists of 20x20 equally sized, square patches. During initialisation 20 patches are randomly selected and populated by agents. On each selected patch we initialise 20 agents forming a neighbourhood agent group. Agent types are defined by preference profiles according to HAPPenInGS which are represented in the agents' persistent state variables (see section 3.2.7.2). For heterogeneous populations the relative ratio between agent types is preserved on the level of neighbourhood groups. For all agents the investment state variable is initialised to 0.0.

After setting up the agents in the environmental context, the social network is initialised. We use a directed network where a link from agent A to agent B means that B is influenced by A. In the model, the investment behaviour of A is perceivable by B and contributes to B's evaluation of its social conformity goal along with the behaviours of all other agents having outgoing social network links to B (see section 3.2.7.2). We use a stylised version of the network initialisation process proposed in Holzhauer, Krebs, and Ernst (2011, 2012) which is discussed in further details in section 4.4.5.3: To account for baseline homophily we link each agent to 5 randomly selected agents from its neighbourhood group. To account for

inbreeding homophily each agent is in addition linked to 5 agents of the same agent type selected at random from the full population.
The initial settings of the global variables of the sub models are documented in section 3.2.7.

3.2.6 Input Data

The model does not require time series of empirical input data.

3.2.7 Submodels

3.2.7.1 Environmental context: Algorithmic Representation of the Public Good

It is assumed that each local agent group has n members and that group size remains constant over time. In each time step the level of the public good on a patch is calculated from the contributions of the members of the providing group. An agent's contribution is represented as a real number x ($0 \leq x \leq 1.0$) where x is one of 11 distinct behavioural options that reflect investments of 0.0, 0.1 up to 1.0 in steps of 0.1. Based on the contributions of the n agents we determine the level of the generated public good following Equation 1 (adapted from Janssen & Rollins, 2009). In the equation parameter m is the minimum number of agents required to provide the full extent of the public good. Parameter γ describes the shape of the investment-success-curve. For low individual investments x_i the value of c is close to 0. For high values of x_i (for all i) and reasonably large γ c approaches 1.0.

$$c = \frac{\left(\sum_{i=1}^{n} x_i\right)^{\gamma}}{\left(\sum_{i=1}^{n} x_i\right)^{\gamma} + \left(\frac{m}{2}\right)^{\gamma}}$$

Equation 1. Level of the public good c generated by n agents. Agent i contributes x_i. At least m agents are required to provide the full extent of the public good.

Figure 6 shows the curve for $\gamma=5$ (which is used in the simulations). The curve describes a continuous version of a step-level public good (Suleiman, 1997). Substantial levels are only generated for average individual investments above 0.15 (i.e. for a group of 20 above a group investment of 3.0 units). The success of support approaches 100% if the mean of individual contribution reaches at least 0.4 (group investment of 8.0 units in a group of 20).

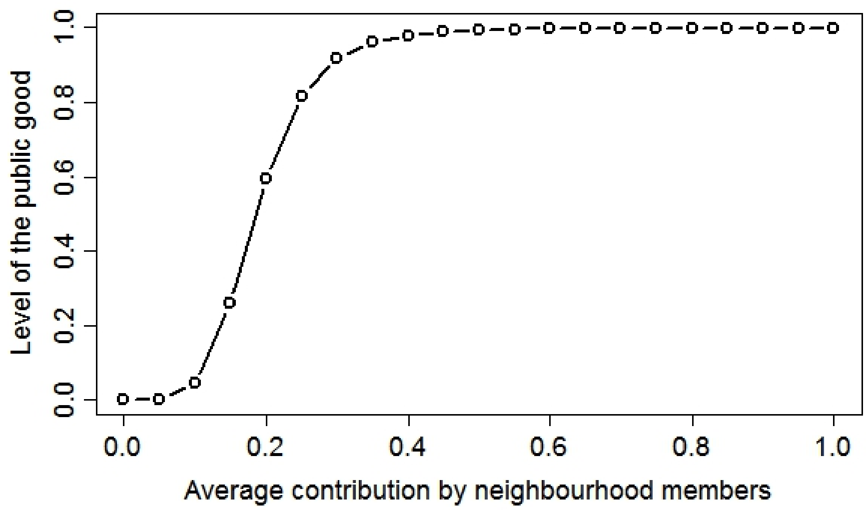

Figure 6. Level of the public good generated by 20 agents (n=20, γ=5, m=7).

Notice that Figure 6 relates the mean investment of all group members to the level of the PG. As for the success of the PG provision only the sum of the investments of all group members is crucial, unequally distributed contributions may yield identical success. A case of free riding would occur e.g. if substantial levels of the public good were provided by a majority of group members and a minority refuses to invest but shares in the obtained social benefit.

3.2.7.2 Agent Decision-Making: Deliberation and Exploration

HAPPenInGS forms the theoretical framework of deliberative agent decision-making in HAPPenInGS-A. Accordingly, an agent's selection of a behavioural option is guided by the three preferences stated by the theory which are shown in the second column of Table 2. These preferences reflect the sensitivity of the agent to particular objectives, i.e. which objectives are given priority over others. An agent's knowledge about the effectiveness of its behavioural options is represented by a utility calculation which relates the perceptions of an agent and its expectations about the outcome of executing a behaviour to the agent's subjective preferences.

In HAPPenInGS-A, agents use this subjective utility to assess, compare and rank their behavioural options based on their preferences and perceptions. To do so, each agent perceives the present success of the collective action, i.e. the level of the public good provided by its respective group, and supposes that the n-1 other agents of its group keep to their previous investment decisions in the next time step. Thus, each agent can estimate the new success of the collective action associated with each of its possible next investment decisions. Moreover, an agent perceives the average level of contributions within its group. Finally, agents refer to their social network and determine the average level of contributions by their peers. Table 2 gives an overview of the preference structure along with an example preference set. Based on their preference set, agents can determine the expected utility of each investment option x. The expected subjective overall utility of investment option x is calculated by adding up the criteria values for a given x weighted by the respective preference value.

#	HAPPenInGS preference	Preference parameter (example value)	Criterion
1	Public good	*publicGoodImportance* (1.0)	c(x)
2	Distribution of investments	*egoisticTendency* (0.1)	1.0 – x
3		*altruisticTendency* (0.3)	1.0 - mean x of other group members
4	Social conformity	*socialConformityImportance* (0.1)	1.0 - abs(x - mean x of peers)

Table 2. Preferences according to HAPPenInGS, the respective parameters, and assessment criteria along with an example preference set. An agent's preferences are weighting factors for the criteria. Agents may e.g. differ in the way they satisfy preference 1 depending on their subjective balancing between preferences 2 and 3 which allows representing social orientations (see section 2.1.2.1). An agent's preference to behave in a way that conforms to the behaviour of its important peers in its social network is reflected in preference 4. The last column displays the formulas used to calculate an agent's estimation of the satisfaction

of a given preference. Here x is the investment level of the behavioural option evaluated, c(x) stands for the expected level of the public good, abs() calculates the absolute value.

The formula used to calculate the expected utility u of an investment option x is displayed in Equation 2.

$$u(x) = publicGoodImportance \times c(x) + egoisticTendency \times (1 - x) \\ + altruisticTendency \times (1 - mean\ x\ of\ other\ group\ members) \\ + socialConformityImportance \times (1 - abs(x - mean\ x\ of\ peers))$$

Equation 2. Expected utility of investment option x. In the formula c(x) is calculated according to Equation 1.

For deliberative decision-making, the final selection of an investment option is represented by a probabilistic choice model (see e.g. Janssen & Ahn, 2006) based on the expected utilities (see Equation 3).

$$P(x_{j,t} = k) = \frac{u(x_j = k \mid x_{\underset{i \neq j}{i}} = x_{i,t-1})^{\eta}}{\sum_{l \in M} u(x_j = l \mid x_{\underset{i \neq j}{i}} = x_{i,t-1})^{\eta}}, k \in M$$

Equation 3. Probability that agent j takes investment decision k in time step t. Agents choose between 11 investment levels from the discrete set M={0.0, 0.1, …, 1.0}. Parameter η allows for calibrating the distinction between the decision options.

Exploration is modelled by allowing agents to select a random investment level (uniformly distributed).

3.3 Dynamical Analysis

The main goal of this section is to document and validate macro-level patterns generated by HAPPenInGS-A. Such patterns constitute and describe the collective as well as the temporal-dynamic implications of the HAPPenInGS theory. Hence, we apply ABSS in the classical context of theory validation as discussed in sections 2.2.1 and 2.2.2 respectively. In addition, we draw on the identification of suitable ranges for the preference parameters for the use in case-specific model parameterisation. The work presented here substantially extends previously reported results (Krebs & Ernst, 2010).

3.3.1 Homogenous populations without social influence

We first report on the influence of the agents' social orientation (i.e. the weighting between *egoisticTendency* and *altruisticTendency*) on agent behaviours and on the success of the collective action. This is done in terms of a sensitivity analysis of the respective preference parameters of HAPPenInGS-A. For this sensitivity analysis we set the preference for social conformity to 0 (*socialConformityImportance*=0.0*)*, i.e. agents disregard social influences. Scenarios including social influences are presented in sections 3.3.2 and 3.3.3 respectively.

Table 3 shows the parameter ranges considered. In total 81 different social orientations (9x9 combinations of *egoisticTendency* and *altruisticTendency*) are investigated. Furthermore, we assume identical preference profiles for all agents, i.e. identical settings of the preferences parameters according to HAPPenInGS. For each social orientation 20 independent simulations over 400 time steps were performed (different random seed initialisations).

Preference parameter	**Value**
publicGoodImportance	1.0
egoisticTendency	0.0 to 0.4, resolution 0.05
altruisticTendency	0.0 to 0.4, resolution 0.05
socialConformityImportance	0.0

Table 3. Agent preference settings used in the sensitivity analysis.

Results of the model runs are reported in terms of three performance indicators:

- The average success of the agent groups in providing the public good.
- Agent behaviours in terms of contributions to the PG provision.
- The Gini index of contributions.

For each run we calculate mean values of the indicators for each tick. These mean values are calculated over all agents of the population for the two behaviour-related indicators and over agent groups for the success of the PG provision. Then, we aggregate these values to mean values over all simulation ticks. Finally, for the visualisation in the diagrams we calculate mean values of these aggregations over all 20 initialisations. The following figures show the results of the sensitivity analysis, i.e. the averaged outcomes of 400 decisions cycles by each of the agents.

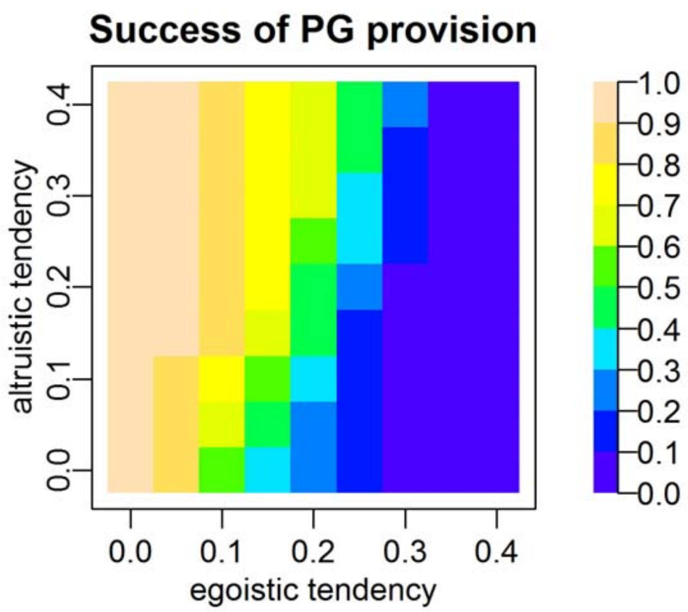

Figure 7. Success of PG provision for the case of deliberative decision-making in homogenous populations without social influence: Each square represents mean values over 400 ticks and 20 runs with a fixed parameter setting but different random initialisations for *publicGoodImportance*=1.0, *socialConformityImportance*=0.0. Abscissa shows *egoisticTendency*, ordinate *altruisticTendency*.

Figure 7 shows that if egoistic preferences are high (*egoisticTendency*>0.3) no substantial levels of the public good are generated independent of the weight put on altruistic tendencies (*altruisticTendency*). For lower egoistic tendencies the level of the public good grows with increasing altruistic preferences. Vice versa for fixed altruistic tendencies the public good decreases with increasing consideration of an agent's own investments. For *egoisticTendency*=0.0 the highest level is achieved – agents only strive for high levels of the public good (*publicGoodImportance*=1.0) disregarding their contribution level. Contributions even exceed the maximum required investment (see Figure 6) to achieve full level of the public good (see Figure 8). When agents take contributions of other group members into consideration (*altruisticTendency*>0.0) random changes in the contribution level by other agents ("experimentation") trigger a "re-thinking" of investments which in the long run reduces investments (still remaining on a high level). For *egoisticTendency*>0.0 contributions always increase when *altruisticTendency* increases - it becomes more attractive to invest in order to reduce the investments required by others.

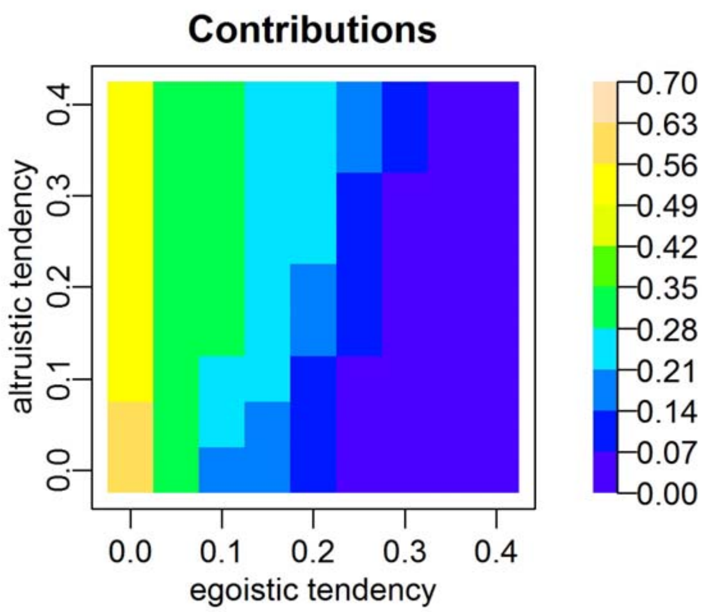

Figure 8. Individual contributions to PG provision for the case of deliberative decision-making in homogenous populations without social influence: Each square represents mean values over 400 ticks and 20 runs with a fixed parameter setting but different random initialisations for *publicGoodImportance*=1.0, *socialConformityImportance*=0.0. Abscissa shows *egoisticTendency*, ordinate *altruisticTendency*.

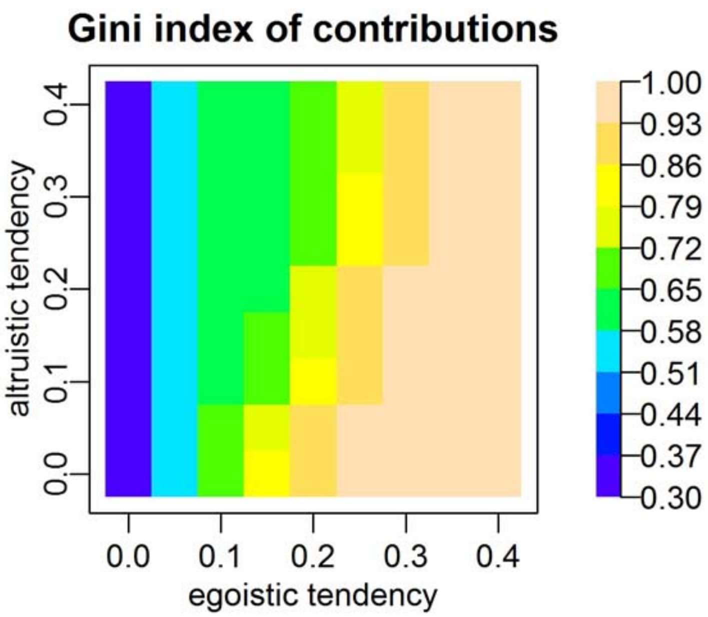

Figure 9. Gini index of individual contributions to the PG provision for the case of deliberative decision-making in homogenous populations without social influence: Each square represents mean values over 400 ticks and 20 runs with a fixed parameter setting but different random initialisations for *publicGoodImportance*=1.0, *socialConformityImportance*=0.0. Abscissa shows *egoisticTendency*, ordinate *altruisticTendency*.

Finally, Figure 9 illustrates that the Gini index of the contributions increases with increasing *egoisticTendency*. Likewise it decreases with increasing *altruisticTendency*. Highest inequality is observed in areas where the public good is not provided – mainly zero contributions but isolated and unsuccessful experimentation (random decisions).

In summary, the sensitivity analysis shows that the model plausibly describes the macro-level outcomes of micro level preferences assigned to the agents. The sensitivity analysis demonstrates how ranges in the two-dimensional space of individual social orientations map to macro-level indicators like the level of the PG. In particular, the sensitivity analysis allows identifying prototype parameter combinations representing three basic types of agents with regard to social orientation:

- **Altruistic agents** stress altruistic tendencies relative to egoistic tendencies (*egoisticTendency*=0.1*, altruisticTendency*=0.3*)*. In average, these agents show contributions up to 0.42 and achieve high PG levels between 0.8 and 0.9.

- Vice versa **egoistic agents** stress egoistic tendencies (*egoisticTendency*=0.3*, altruisticTendency*=0.1*)*. For this type, average contribution levels do not exceed 0.07 yielding negligible PG levels between 0.0 and 0.1.
- A third social orientation preference may be found for **neutral agents** with a balanced weighting between altruistic and egoistic tendencies (*egoisticTendency*=0.2*, altruisticTendency*=0.2*)*. Contribution levels of this agent type in average can go up to 0.21 while the average level of the PG does not exceed 0.6.

The three basic agent types are to be understood as discrete representatives of ranges of parameter combinations in HAPPenInGS-A which lead to qualitatively similar macro-level outcomes. Altruistic and egoistic types are located at the two extreme ends of the spectrum of social orientations that are covered by HAPPenInGS-A. The neutral type represents the transition range of parameters between the extremes.

The sensitivity analysis of this section has disregarded social influences by setting the importance of the social conformity preference to 0 for all agents. The next section explicitly analyses the effect of increasing the weight put on the social conformity preference in populations that are homogeneously composed of one of the three basic agent types.

3.3.2 Homogenous populations with social influence

This section investigates the interplay of social orientation and social conformity in HAPPenInGS-A for the case of homogenous populations, i.e. populations where all agents have identical preference profiles. The preference sets considered in this sensitivity analysis combine the three prototype social orientation preferences which have been identified in the previous section with different importance settings for social conformity preference. The parameter ranges investigated are documented in Table 4. Accordingly, we investigate six preference sets for each basic agent type which differ in the respective importance of the social conformity preference. Note that the case *socialConformityImportance*=0.0 from the previous section is included in the results. Again, for each combination of parameter settings 20 independent runs over 400 steps are performed.

Basic agent type	**Preference set**			
	publicGood-Importance	*egoisticTendency*	*altruisticTendency*	*socialConformity-Importance*
Altruist	1.0	0.1	0.3	0.0 to 0.5, resolution 0.1
Neutral	1.0	0.2	0.2	
Egoist	1.0	0.3	0.1	

Table 4. Agent types and respective preference sets used in the sensitivity analysis. Three basic types of agents regarding social orientation are investigated. For each basic type six different settings for the social conformity preference are considered.

Simulation results are reported with respect to three different indicators:

- Agents' behaviours in terms of their mean contribution (black).
- Agents' achieved social conformity as the mean value of their perceived social conformity (red). For each agent the social conformity perception is calculated according to the criterion formula for preference #4 in Table 2. It reflects an agent's absolute attainment of its social conformity preference.
- The success of the collective action as the mean level of the PG of all groups (green with error bars of one standard deviation).

The first set of diagrams compares the performance of homogeneous populations of the three agent types with increasing importance of the social conformity preference. To assess performance we calculate means of the indicators during the last 200 steps for each run. In the diagrams we show the mean values of these aggregations and standard deviations of the 20 initialisations used.

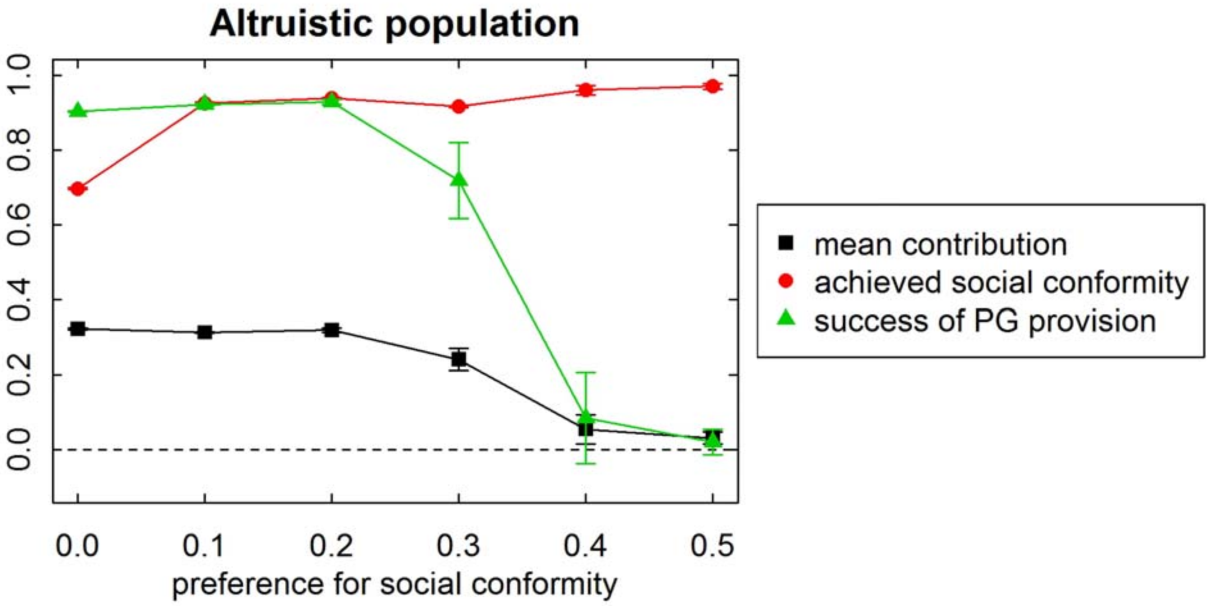

Figure 10. Aggregated results of the sensitivity analysis for altruistic agents. For each run performed we calculate the mean values of three different performance indicators during the last 200 simulation steps. In the diagrams the error bars show the standard deviation of the mean values of the 20 runs performed for a distinct parameter setting. See text for further explanation.

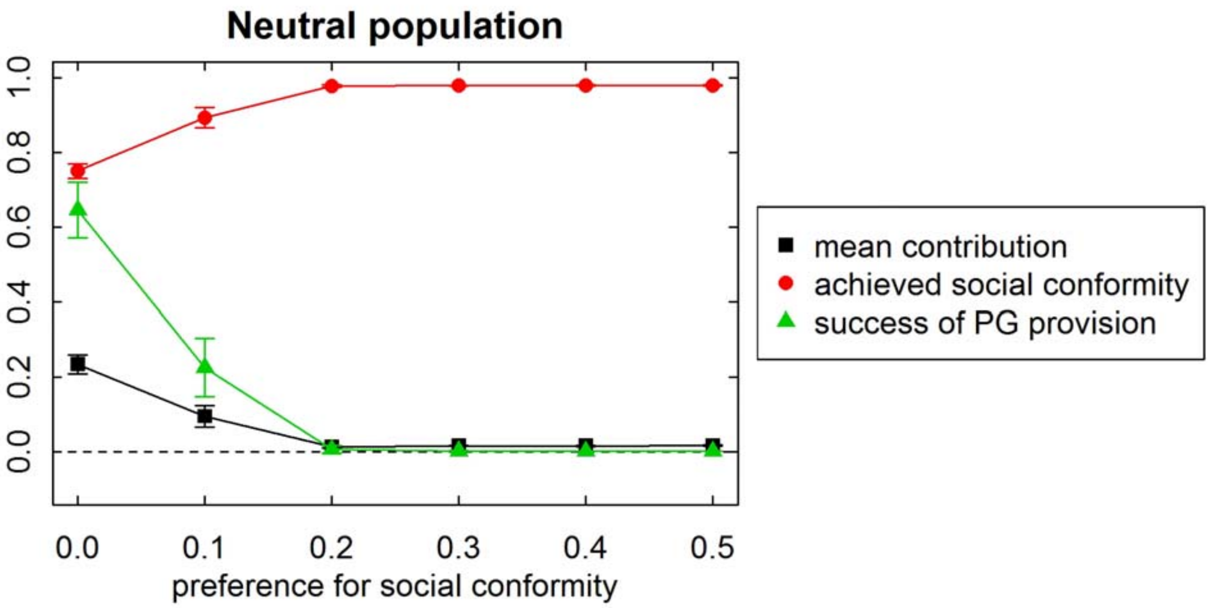

Figure 11. Aggregated results of the sensitivity analysis for neutral agents. For each run performed we calculate the mean values of three different performance indicators during the last 200 simulation steps. In the diagrams the error bars show the standard deviation of

the mean values of the 20 runs performed for a distinct parameter setting. See text for further explanation.

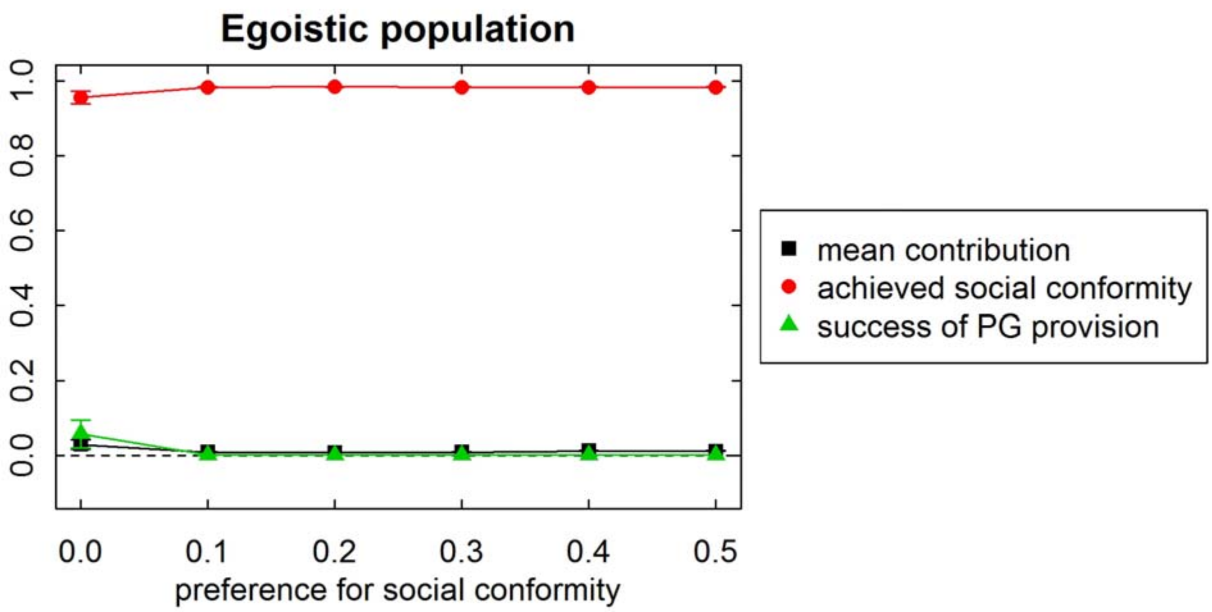

Figure 12. Aggregated results of the sensitivity analysis for egoistic agents. For each run performed we calculate the mean values of three different performance indicators during the last 200 simulation steps. In the diagrams the error bars show the standard deviation of the mean values of the 20 runs performed for a distinct parameter setting. See text for further explanation.

As a general pattern for all three types of social orientations we observe that with increasing importance of social conformity indeed the social conformity perceived by the agents rises and settles close to the maximum level of 1. Clearly, this demonstrates that agents manage to satisfy the social conformity preference in addition to their other preferences. However, when relating this observation to behaviours of the agents we see clear differences between the three types.

For egoists low contributions are reinforced as a social norm when the importance of social conformity during agent decision-making increases (see Figure 12). This is mainly due to the homogeneous settings of agent behaviours during model initialisation which sets investment levels to 0 for all agents (see section 3.2.5). These settings are well in line with egoistic social orientations and in addition provide initially high local conformity perceptions. Therefore, the passive social norm of low contributions persists throughout the simulation in the egoistic population.

For the altruistic population (Figure 10) we observe more diverse dynamics: Altruistic agents manage to achieve high contribution levels and provide high levels of the PG along with increasing social conformity perceptions until the importance of social conformity exceeds 0.3. Obviously, when comparing to the egoistic case, in the altruistic population a different social norm emerges until the importance of social conformity goes beyond this threshold. For higher preferences for social conformity even altruists show the same lock-in of passive behaviour as egoists – the high weight of the social conformity preference dominates altruistic preferences during decision-making and therefore inhibits initial mobilisation. For neutrals we observe a similar behaviour intermediate to that observed for the other two types (see Figure 11).

The following analysis investigates the case of the altruistic population in more depth. We examine the temporal dynamics underlying the described aggregated observations and introduce two additional performance indicators:

- The standard deviation of agent behaviours within a population (vertical dashed, black).
- The temporal stability (convergence) of agent behaviours as the total decrease or increase of contribution relative to the previous time step on the individual level (delta contribution, blue).

Results are reported in terms of mean values of the respective 20 runs performed per simulation tick. Furthermore, we pick three distinct settings for the weight of the social conformity preference during decision-making: In Figure 13 we display simulation results for *socialConformityImportance*=0 which reflects the extreme case where social networks have no influence in the decision process. In the aggregated simulation results discussed above (see Figure 10) we find that for a medium setting for the importance of social conformity (*socialConformityImportance*=0.2) success of the PG provision and the achieved social conformity have their maxima. Therefore, we pick this setting for a second in-depth analysis that is shown in Figure 14. Finally, Figure 15 displays results for the extreme case of *socialConformityImportance*=0.5.

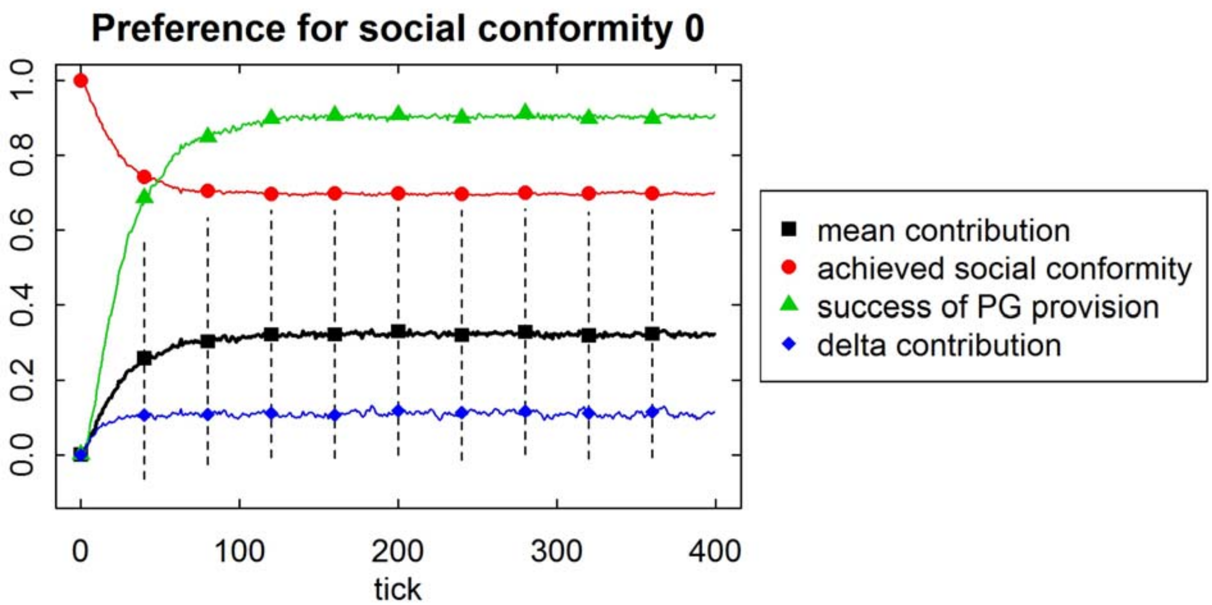

Figure 13.Temporal dynamics for altruistic agents and preference for social conformity 0. We show mean values of the respective 20 runs performed per simulation tick. See text for further explanation.

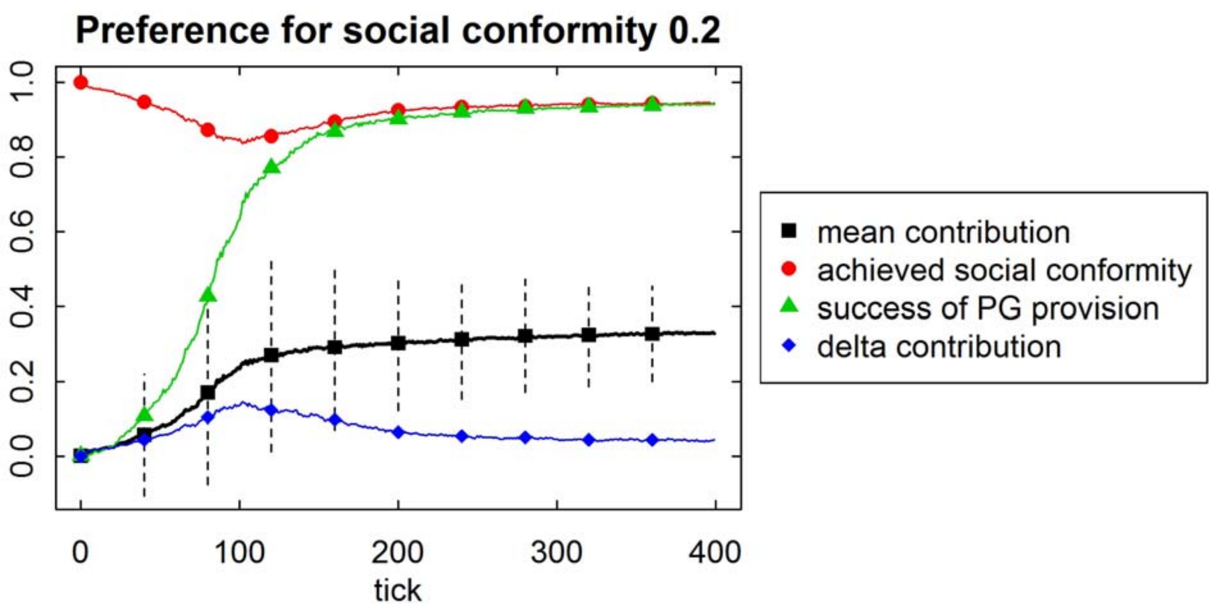

Figure 14. Temporal dynamics for altruistic agents and preference for social conformity 0.2. We show mean values of the respective 20 runs performed per simulation tick. See text for further explanation.

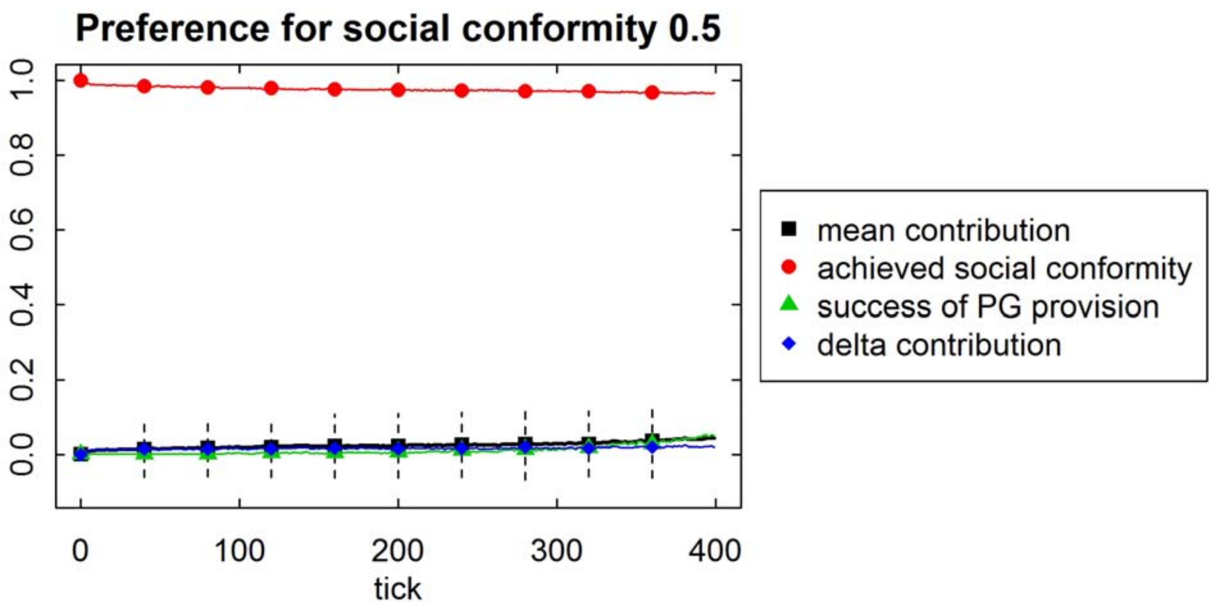

Figure 15. Temporal dynamics for altruistic agents and preference for social conformity 0.5. We show mean values of the respective 20 runs performed per simulation tick. See text for further explanation.

In all three figures above, due to the homogeneous initialisation of the agents with zero contributions, the social conformity perceived by the agents starts on the maximum level during the initial simulation steps. If the preference for social conformity is high (Figure 15) this passive social norm is sustained throughout the simulation and social mobilisation does not take place. For more moderate preferences for social conformity we observe successful social mobilisation (Figure 13, Figure 14). In both cases the achieved social conformity drops during the initial phase of social mobilisation. For the first case (preference for social conformity 0) the maximum success of PG provision is reached after 150 ticks and sustained until the end of the simulation. In contrast, for the moderate social conformity preference (Figure 14) mobilisation proceeds slower but continuously improves towards the end of the simulation. This slow-down of social mobilisation may be attributed to an on-going process of social adjustment: Clearly, compared to Figure 13, in Figure 14 the achieved social conformity does not drop as steeply and instead continues to increase during the simulation after tick 100. Likewise, for the medium social conformity setting in Figure 14 we observe a decrease of the standard deviation of the contributions (dashed black) which does not occur for the low social conformity setting in Figure 13. An additional difference between simulations with low and medium settings for the social conformity preference lies in the development of the behavioural stability indicator (delta contribution in blue) that reflects the individual change in behaviour between two consecutive simulation ticks: While under both settings contributions settle around a mean of 0.3, in the absence of social conformity preferences individual behaviours appear to fluctuate significantly (around 0.1) from one tick to the next throughout the simulation, i.e. agents continuously adjust their behaviour. With medium social conformity preference this effect is dampened and delta contribution approaches zero over time. Apparently, the striving for social conformity not only decreases the spread of behaviours within the population; it also decreases the spread of behaviours selected by one agent over time.

The following section goes a step further and reports on simulation results for agent populations with heterogeneous preference profiles.

3.3.3 Heterogeneous populations with social influence

This section investigates the interplay between social conformity and social orientations in heterogeneous agent populations. We set up populations with different ratios of altruistic agents and egoistic agents, and different (population) global settings of the social conformity preference. The investigated parameter combinations are documented in Table 5. Again, for each population composition and parameter settings 20 independent runs over 400 steps are performed.

Basic agent type	**Preference set**				**Proportion of agents in population**
	publicGood-Importance	*egoistic-Tendency*	*altruistic-Tendency*	*socialConformity-Importance*	
Altruist	1.0	0.1	0.3	0.0 to 0.2, resolution 0.1	0.1 to 0.9, resolution 0.1
Egoist	1.0	0.3	0.1		1 – proportion of altruists

Table 5. Agent types, respective preference sets and population composition used in the sensitivity analysis. Two basic types of agents regarding social orientation are investigated.

For each basic type three different settings for the social conformity preference are considered. For each preference set a total of 9 population compositions is investigated.

Results are reported with respect to the following extension of three of the performance indicators introduced in the previous section:

- Agents' behaviours in terms of their mean contribution (black), mean contributions of altruistic agents (dashed black), and mean contributions of egoistic agents (dotted black).
- Agents' achieved social conformity as the mean value of their perceived social conformity (red) and the respective means for altruistic and egoistic agents (dashed respectively dotted red).
- The success of the collective action as the mean value of all groups (green).

In the diagrams, we compare the performance of heterogeneous populations with increasing social conformity preference. To assess performance we calculate means of the performance indicators during the last 200 steps for each run. In the diagrams we show the mean values of these aggregations and standard deviations of the 20 initialisations used.

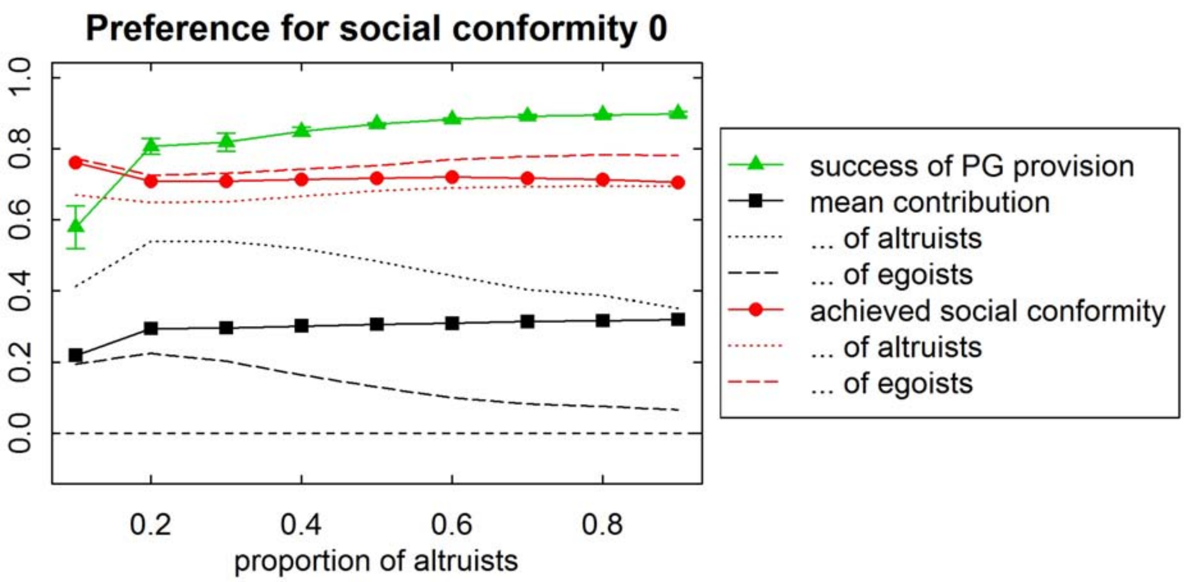

Figure 16. Aggregated results for different population compositions and preference for social conformity 0. For each run performed we calculate mean values of the performance indicators during the last 200 simulation steps. The error bars show the standard deviation

of the mean values of the 20 runs performed for a distinct parameter setting. See text for further explanation.

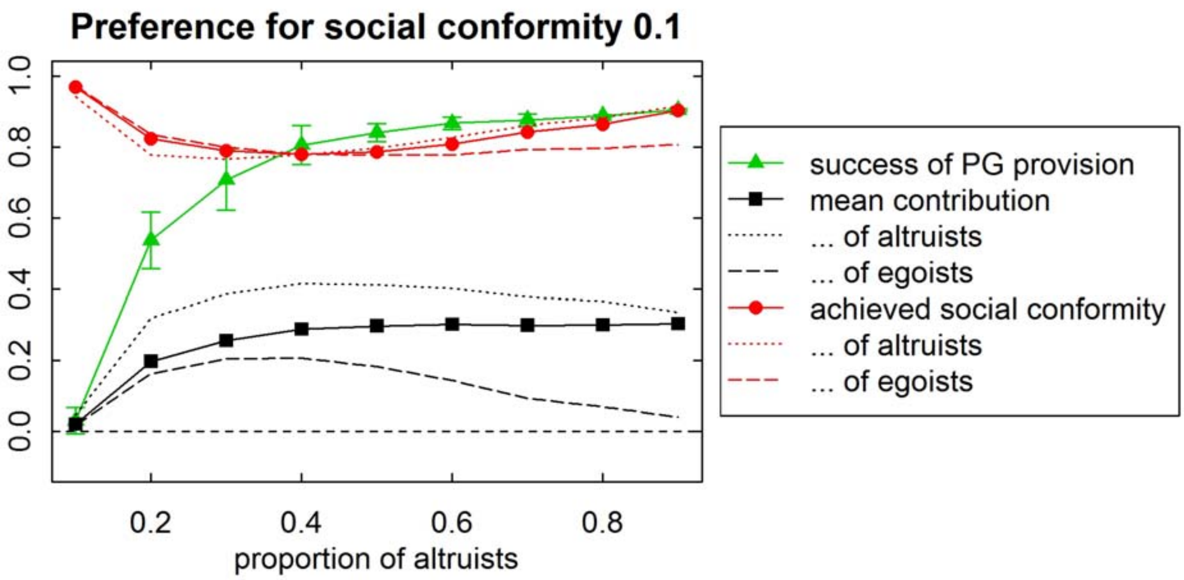

Figure 17. Aggregated results for different population compositions and preference for social conformity 0.1. For each run performed we calculate mean values of the performance indicators during the last 200 simulation steps. The error bars show the standard deviation of the mean values of the 20 runs performed for a distinct parameter setting. See text for further explanation.

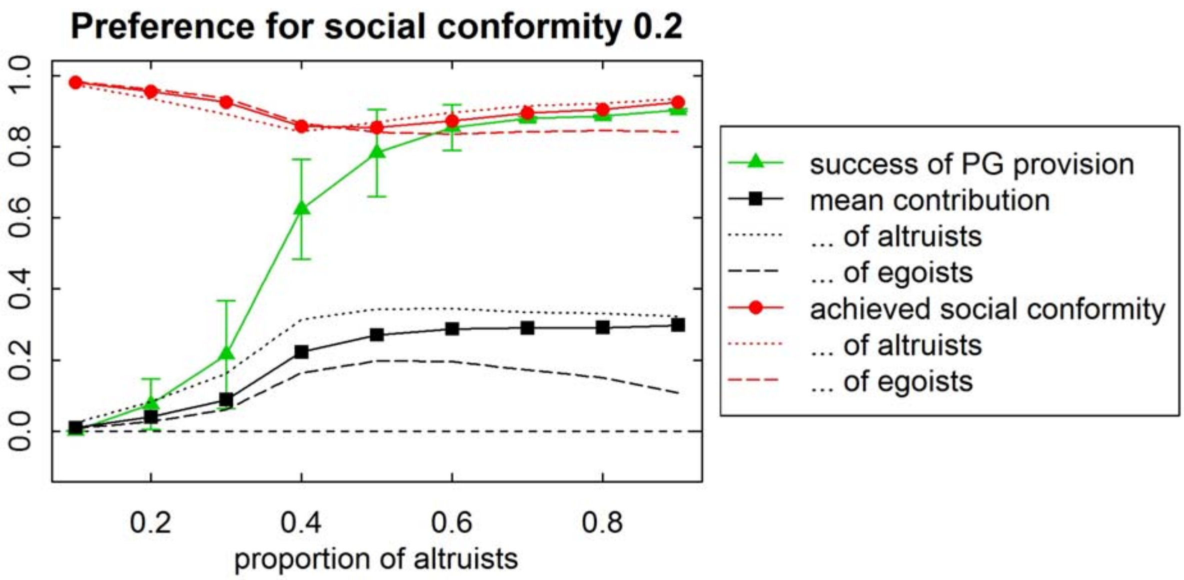

Figure 18. Aggregated results for different population compositions and preference for social conformity 0.2. For each run performed we calculate mean values of the performance indicators during the last 200 simulation steps. The error bars show the standard deviation of the mean values of the 20 runs performed for a distinct parameter setting. See text for further explanation.

Unsurprisingly, in all three diagrams above we observe that the success of the collective action generally increases with increasing proportion of altruists. However, significant differences exist depending on preference weight of social conformity.

For the lowest setting for social conformity we observe that when the proportion of altruists is at least 0.2 the success of the PG provision reaches high levels (Figure 16). Even if 90% of the population are egoists, a moderate PG level of around 0.6 is provided.

When the preference weight of social conformity increases, the proportion of altruists required for achieving high levels of the PG increases: In Figure 17 high levels of the PG are provided for populations with at least 40% of altruistic agents. Likewise, in Figure 18 more than 50% of altruists are required. Apparently, social coherence effects inhibit mobilisation due to a lock-in of passive behaviour with increasing preference for social conformity and with decreasing proportion of altruists. Especially for highest preference for social conformity we observe that the altruists show investment behaviours that obviously contradict their social orientations: For the social conformity preference 0.2, if the size of the altruistic subpopulation does not exceed 30% of the population, altruists contribute less than 0.15 (see Figure 18). However, such behaviour yields high social conformity in a predominantly egoistic population (see Figure 18) which apparently overrides individual social orientations during agent decision-making.

Finally, it may be seen that the inequality of behaviours between altruists and egoists decreases when preference for social conformity increases. As a result, altruists tend to contribute less and egoists tend to contribute more with increasing social conformity preference. Clearly, when the preference for social conformity gains importance during agent decision-making, the topology of the social network increasingly influences investment behaviours. Therefore, prevalent behaviours of the respective other subpopulation contribute more to an individual's social conformity perception and in turn trigger a process of inter-population social adjustment.

3.3.4 Synthesis of results

The focus of the HAPPenInGS theory is the micro-level of decision-making in public good dilemmas. The purpose of HAPPenInGS-A is to supplement the bottom-up macro-level perspective on public good provision by applying methods of ABSS. In doing so, HAPPenInGS-A represents processes of social influence, temporal dynamics, and collectives of agents each behaviourally grounded in HAPPenInGS.

The key question of this section was on the interrelation of individual-level preference profiles and macro-level outcomes. We tackled the question by exploring the range of implications of the HAPPenInGS theory through a series of simulation exercises.

The presented set of consecutive simulation experiments started in section 3.3.1 by investigating the range of possible social value orientations in the scope of HAPPenInGS in the absence of social influences. The sensitivity analysis confirmed that populations of agents which stress altruistic considerations during decision-making are indeed successful in providing a public good while egoistic populations constantly fail. Furthermore, simulations with HAPPenInGS-A allowed identifying transitions of collective behaviour in relation to different social orientation parameter combinations. Section 3.3.1 concluded by stating suitable parameter settings for prototype preference profiles of altruistic, egoistic and neutrally oriented agents respectively. The first two types can be seen as HAPPenInGS counterparts of prosocials and proselfs as found in experimental work on PG dilemmas (see section 2.1.2.1) while the latter agent type characterises the transition range of parameters between the extreme parameterisations of HAPPenInGS.

Section 3.3.2 analysed the interplay of social orientation and social conformity in HAPPenInGS-A. As a main result, simulations showed different facets of social coordination: High preferences for social conformity can override individual altruistic orientations and inhibit social mobilisation – a passive social norm emerges.

In altruistic populations, moderate preferences for social conformity yield high PG levels and in addition decrease the spread of behaviours within the population. Furthermore, social conformity preferences reduce behavioural volatility on the individual level. However, mobilisation proceeds slower if agents strive for social conformity – social adjustment takes time.

Both sections 3.3.1 and 3.3.2 investigated populations of agents that are homogeneous in their preference profiles. However, in particular the analysis of the time series of simulation runs illustrated that despite this homogeneity of agent preferences notable variation of individual behaviours within a population exists. In HAPPenInGS-A this inherent diversity is due to sources of heterogeneity that are typical for ABSS: During initialisation, agents are randomly embedded in a social network and randomly assigned to agent groups. Both aspects of initialisation imply subjective perceptions and opportunities of behaviours for individual agents.

Finally, in the simulations presented in section 3.3.3, we increased heterogeneity by considering populations composed of different percentages of altruistic and egoistic agents. The main conclusion from the simulations is that in HAPPenInGS-A social influences decrease the inequality of behaviours between the altruistic and the egoistic subpopulations. As a result of social adjustment agents show behaviours that can deviate from their social preferences: Altruists tend to contribute less and egoists tend to contribute more when their social conformity preference increases.

3.4 Concluding summary

This chapter carried forward the insights and implications from the literature review of chapter 2 into theory and method development. Section 3.1 outlined HAPPenInGS as a theoretical model of preference-guided action selection in public good dilemmas and confirmed that HAPPenInGS is in line with the requirements derived in the synthesis sections of the literature review. Section 3.2 contributed the integration of the theory in an ABSS exercise. The purpose of HAPPenInGS-A was to provide a middle-range ABSS reflecting the core properties and dynamics of the problem domain and to perform a systematic analysis of the collective behavioural dynamics and macro-level patterns implied by the HAPPenInGS theory.

The contribution of section 3.3 had two major components: Firstly, the sensitivity analysis of HAPPenInGS-A allowed to assess the general plausibility and consistence of the HAPPenInGS theory in an ABSS context. Here, we demonstrated the interplay between social orientation and social conformity preferences on the micro level, and the effect on macro level indicators. Secondly, we identified suitable parameter ranges for case-specific parameterisation of the HAPPenInGS-A. In particular, we extracted prototype preference sets for three different agent types. Especially, this second contribution (see section 3.3.4) will play an important role in the following chapter where we will instantiate HAPPenInGS-A for a case study.

4 Modelling neighbourhood support in Northern Hesse

In the previous chapter we presented an abstract ABSS and demonstrated the principle plausibility of HAPPenInGS in describing preference-guided decision-making in public good dilemmas. This section goes a step further and applies HAPPenInGS in a real world case study context of public good provision. From a methodical point of view we demonstrate how the abstract HAPPenInGS-A may be instantiated for a specific case by linking it to real world empirical data.

The empirical context of this chapter is climate change adaptation for the case of the Northern Hesse region located in the centre of Germany. One important adaptation requirement will be volunteering activities for local neighbourhood support in order to supplement public health care during heat waves. We report on a spatially explicit ABSS model setup in which the agent population is initialised from large scale spatial explicit socio-empirical data. In doing so, the lifestyle composition found in the empirical data is mapped to preference profiles of the agents according to HAPPenInGS. We present modelling results and motivate how simulations may support the formation of health policies. As a result we identify (areas with) populations with low potential for self-organised neighbourhood help and such with potentially well working neighbourhood support. Furthermore, we investigate two different intervention scenarios that aim on mobilising passive subpopulations. Results of the presented scenario assessment may be used to inform policy makers and stakeholders on possible targets of information campaigns and will provide insights into the interplay of barriers and incentives regarding the individual action of adaption to climate change and their trajectories.

The work presented in this chapter was conducted during the KUBUS[2] project (Unterstützung der regionalen Klimaanpassung durch Umweltsozialwissenschaftliche Befragung Und Szenarienbildung - english: Supporting regional climate change adaptation by means of socio-environmental surveys and scenario development). We report on results which were previously published in (Krebs et al., 2011) and (Krebs et al., 2013).

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[2] We wish to thank the German Federal Ministry of Education and Research (BMBF) for funding under grant number 01LR0809A.

This chapter is organised as follows: Section 4.1 outlines the project context in which the presented research was conducted. A subsequent section provides a brief overview of the problem domain of health care under conditions of climate change, extracts the central problem features to be covered in the model, and links these to social dilemma research. Section 4.3 substantiates the embedding in social dilemma research by describing the decision situation of potential volunteers for neighbourhood support in the context of HAPPenInGS. Section 4.4 provides the ODD description of the ABSS developed and section 4.5 documents the simulation results. The last section discusses and provides an outlook on future work.

4.1 Project context and introduction

KUBUS belongs to "KLIMZUG-Northern Hesse" (KLIMZUG-Nordhessen, 2009), the transdisciplinary network for climate change adaptation in the model region of northern Hesse that develops, implements and tests structures, institutions and procedures for the regional adaptation to climate change. Northern Hesse is located in the middle of Germany with its regional centre, the major city of Kassel, being an important node for both railway and car traffic. Its topology is characterized by low mountain ranges largely covered by woods, and the river Fulda. One million people live on approx. 6,900 km^2, therefore, apart from Kassel, the region is rather sparsely populated and organised at a small scale. Main future challenges for the region comprise the ageing and the decline of the population in rural areas, the expected increase in precipitation during autumn, winter and spring seasons, and extreme weather situations like heat waves, storms, and flooding.

The objective of KUBUS is to contribute to an understanding of the processes of individual adaptation to the consequences of climate change as well as of the public reaction to policy-defined adaptation strategies by means of simulations based on integrated social and policy models. To do so, we investigate possible adaptation of individual behaviour like a change of habit or preventative measures including their acceptance among the socially interacting population. Simulations are empirically grounded by geographically differentiated socio-demographic data of the model region and by quantitative projections from regional climate models.

In this chapter we report on ABSS modelling results on the topic of health care for vulnerable groups under conditions of heat stress. For the target region of Northern Hesse it is expected that in particular increased health care for older people is an important adaptation requirement under conditions of more frequently occurring heat waves caused by climate change. This expectation is backed by a number of medical studies on the health impact of heat waves in European Countries and in the US (Bouchama et al., 2007; Josseran et al., 2009; Semenza, McCullough, Flanders, McGeehin, & Lumpkin, JR, 1999) and by the outputs of regional climate models that anticipate more frequent and more severe heat waves for the modelled region. In addition, due to the projected demographic change in the region it is suspected that a vast majority of the elderly will live solitarily and will have to rely on assistance in case of extreme heat. Experts expect that public health service will likely not be able to provide the required comprehensive and area-wide health care. Therefore, neighbourhood help that supports older people during heat waves is considered as an important local provider of the required care-taking activities.

Neighbourhood support is conceptualised as a public good that requires social mobilisation of local groups of potential helpers in order to work effectively. It is expected that the quality of neighbourhood support differs depending on the prevalent social orientations in the providing group of people in local neighbourhoods. Therefore, our focus lies on the individual decision-making of such group members (represented as agents in the model) on contributing to the generation of the public good.

In the context of the described public good dilemma heterogeneity along social orientations like egoism or altruism along with opinion exchange through social networks play a key role when estimating the potential of local groups of helpers in providing neighbourhood. In the model agents observe the level of the generated public good, the contributions of all other group members to its provision and the behaviour of social network peers. Depending on these perceptions and on the individual social orientation agents continuously adjust their investment in the provision of the public good. The emergent outcome of the modelled decision dynamics provides insights in the potential of local groups of helpers to provide local neighbourhood support depending on the social orientations within such groups. Simulations are empirically grounded by initialising the social orientations within the groups by geo-referenced socio-demographic data.

4.2 Empirical background and motivation

Since the late 1990s there have been a number of medical studies on the specific vulnerabilities of different population groups to temperature extremes (Bouchama et al., 2007; Josseran et al., 2009; Kaiser et al., 2001; Semenza et al., 1999). For instance Semenza, McCullough, Flanders, McGeehin, and Lumpkin, JR (1999) report on the 1995 heat wave in Chicago where the hospitalisation rate due to heat-related sicknesses increased by 11%. The Chicago study shows that especially older people, babies, and children suffer under heat stress. Furthermore, there is evidence for a specific vulnerability of socially isolated individuals. For older people Bouchama et al. (2007), p. 2175 hypothesise that with "appropriate help, the outcome of this vulnerable population, which is composed of individuals who are physically and cognitively impaired and who are thus potentially unable to drink enough fluids, to gain access to cool places without help, or to recognize symptoms of heat exposure during a heat wave, can improve dramatically." An inter-country comparison between the US and France showed that the existence of active neighbourhood networks that provide appropriate help during heat waves significantly decreases the risk of heat-related health damages for solitarily living people in France (Bouchama et al., 2007).

For the region of Northern Hesse there are presently no comparable studies on the health impact of heat waves. Due to demographic change and the predicted climate change the vulnerable group of older people will require increasing attention in the region. Furthermore, due to rural exodus of the younger generation it is expected that the majority of older people will live solitarily as opposed to being integrated in working family networks. Therefore, as the study by Bouchama et al. (2007) suggests, older people will need specific assistance to reduce their risk of health damages during heat waves. As public health service will most probably not be able to provide the required flexible and comprehensive home care neighbourhood help might be an important factor. Potentially, such active neighbourhood support already exists in the target region and it could be activated as a source for flexible assistance for the elderly during heat waves.

The individual help activity of a potential helper consists of visiting a vulnerable person in the neighbourhood and taking care of him or her. Typically, helpers would volunteer and devote some of their free time to helping activities. It is unlikely that a relevant proportion of such help activities result in a persistent one-to-one relationship between helper and needy person because helpers are usually not available for volunteering activities all of the time. Rather, the sum of individual help activities in a neighbourhood is a more relevant indicator for the degree to which neighbourhood support serves as a local substitute or at least a supplement of public health care under extreme weather conditions. Below a certain level of individual investments there will be no noticeable benefit from the neighbourhood support. Above that level the success of the neighbourhood support rises more steeply with increasing individual investments up to a certain maximum. Generally, achieving this optimum does not require maximum investments by all potential helpers. However, well-established neighbourhood support is not only important for needy persons; it is likewise valuable to all potential helpers independent of their respective contribution because the failure of neighbourhood support is well visible and undesired by all members of the group of potential helpers. Therefore, potential helpers face a public good dilemma. Behavioural incentives can be of a material or – more valid here – a psychological nature. More precisely, neighbourhood support has the nature of a step-level public (Suleiman, 1997) that requires a certain "critical mass" of contributions in order to generate any benefit at all and that does not increase in quality if contributions go beyond some threshold. As outlined in chapter 2, such setups give rise to problematic behaviours such as free-riding. In our case potential helpers are in the dilemma of volunteering and actively contributing to the local neighbourhood support vs. being passive and hoping that other group members will generate the public good.

For effective health policy, knowledge of the potential of existing sources of neighbourhood support is crucial. Furthermore, a dynamic ABSS of the formation of neighbourhood support could help to investigate the effects of social mobilisation campaigns for neighbourhoods with low support potential.

4.3 Theoretical embedding (HAPPenInGS-N)

As outlined in the previous section, neighbourhood support for the elderly during heat waves is a public good which is provided by local groups of potential helpers in the locality they inhabit. Hence, the decision-making of the potential helpers on their respective contribution to neighbourhood support is governed by a public good dilemma and may consequently be described by the HAPPenInGS theory. This section specifies the instantiation of HAPPenInGS for the case of neighbourhood support. Figure 19 illustrates the corresponding component overview.

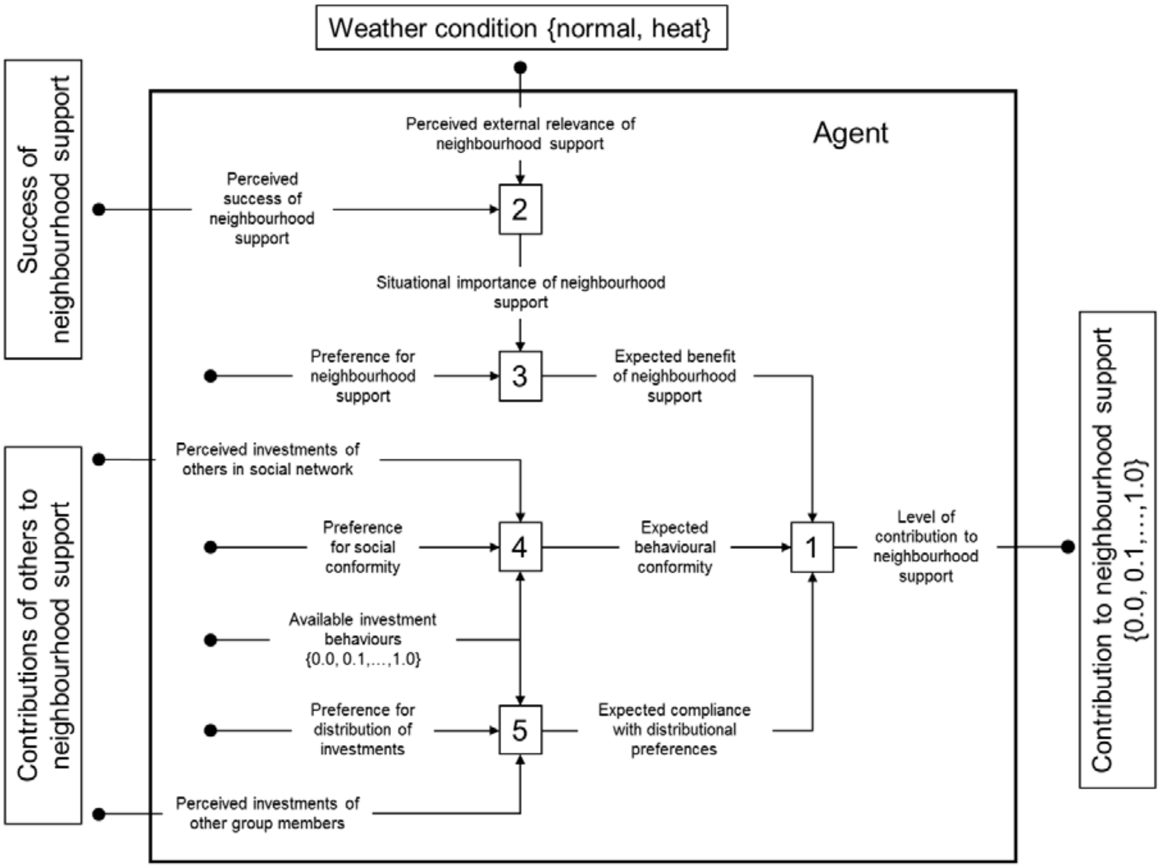


Figure 19. The instantiation of HAPPenInGS for the case of neighbourhood support during heat waves. Arrows show the variables with their names and illustrate the sequence of their processing in the numbered blocks. See text for further explanations.

In order to specify the HAPPenInGS instantiation for the case of neighbourhood support we describe the interfaces of individual decision-making to case-specific representations of the social and environmental contexts. The behavioural target variable is an individual's local *contribution to neighbourhood support* which is executed in the environmental context. On the level of a local helper group these behaviours determine the group's *success of neighbourhood support*, which is the feedback individuals perceive from their environmental context. According to HAPPenInGS, individuals assess this feedback relative to other external conditions. For the case of neighbourhood support this external driver is represented as a temporally varying sequence of local *weather conditions*. We consider heat days and normal weather conditions, and assume that during heat days the situational value of neighbourhood support is high and that it is low otherwise.

In the social context, individual behaviours are exposed to other individuals. Individuals perceive the *contributions of others to neighbourhood support* within their providing group and through the ties of their social network. Group setup and social network composition are case-specific representations of the social context.

4.4 Agent-based social simulation setup for the case of neighbourhood support (HAPPenInGS-N)

This section reports the ABSS setup of HAPPenInGS-N (HAPPenInGS-**N**eighbourhood Support). Model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006; Grimm et al., 2010).

4.4.1 Purpose

The purpose of HAPPenInGS-N is to describe the dynamics of the provision of neighbourhood support during heat waves and the effect of mobilisation campaigns for the city region of Kassel. The goal is to initialise a population of agents from large scale socio-empirical data and to investigate individual decision-making based on HAPPenInGS under the conditions of regional climate projections.

4.4.2 Entities, state variables, and scales

4.4.2.1 Environments

The environmental context represents the locations of the agents on a GIS layer of the city of Kassel. In addition, the environmental context has a temporally varying property representing the daily maximum temperature in the target region. Weather conditions are set globally for the target area at the beginning of a time step in terms of a binary state variable representing either a heat day if the maximum temperature is at least 30° or a normal day otherwise. Finally, the environmental context schedules information campaigns depending on the scenario investigated. Information campaigns are set at the beginning of a time step on the level of neighbourhood group of agents (see 4.4.2.2) and they are represented as a temporally varying binary state variable which is set to true if an information campaign takes place for the respective neighbourhood group and false otherwise.

The social context has a network topology. We initialise a directed social network where a network link from agent A to agent B means that B is influenced by A. In the model, the investment behaviour of A is perceivable by B and contributes to B's evaluation of its social conformity goal along with the behaviours of all other agents having outgoing social network links to B. The social network is set up during initialisation and remains fixed throughout the simulation.

4.4.2.2 Agents

Agents have a fixed spatial location in the environmental context representing the residential neighbourhood of the agent in the target area. An agent's embedding in the social network is represented as a list of other agents which are linked to it by ties of the network.

Agents have four persistent state variables represented as real numbers from the interval [0.0; 1.0] which define their preferences according to HAPPenInGS: While the preference for the public good and the preference for social conformity are each represented by one state variable, the preference for distribution of investments is represented by two state variables quantifying a desired weighting between own contribution and contributions of other group members.

Agents have temporally varying state variables storing the planned investment for the next time step and its expected utility, the last executed investment x, and a memory structure. An agent's memory store collected experiences by associating a situational context and an investment behaviour with the utility which was in average achieved by the behaviour in the context.

Agents are grouped depending on their location in the environment and each such neighbourhood group is characterised by a real number c representing the level of the public good provided by the agents belonging to it. Agents belong to one and only one group.

4.4.3 Process overview and scheduling

Below, we give an overview on the basic processes of the model and the respective triggering. The pseudo code describes the simulation cycle after model initialisation (see section 4.4.5). Each simulation time step starts by setting weather conditions and (depending on the scenario, see section 4.5) by optionally activating an information campaign. Subsequently, for each of the agent groups the local success of neighbourhood support is calculated based on the agents' investment decisions in the previous time step. Next, each agent perceives various attributes of its social and environmental contexts.

Depending on these perceptions and on its internal state (preferences, memorised experiences) each agent selects a decision mode and sets an investment behaviour that will be put into action in the following time step.

```
for each timestep {
  advanceWeatherSequence
  advanceInformationCampaign
  for each neighbourhoodGroup {
    calculateSuccessOfNeighbourhoodSupport
  }
  for each agent {
    perceiveWeather
    perceiveInformationCampaign
    perceiveGroupSuccessOfNeighbourhoodSupport
    perceiveBehaviourOfOtherGroupMembers
    perceiveBehaviourOfNetworkPeers
    if (noCampaignPerceived and confirmedExperienceAvailable) {
      decideByExperience
    }
    else {
      with probability 99% {
        decideByDeliberation
        updateExperiences
      }
      else {
        decideByExploration
      }
    }

  }
}
```

Pseudo code of main simulation cycle.

4.4.4 Design Concepts

This section summarises the main design concepts of HAPPenInGS-N. The concepts according to the ODD protocol are stated in italics.

The *basic principle* addressed by HAPPenInGS-N is collective action for the provision of provision of neighbourhood support in the city area of Kassel. When do heterogeneous groups of individuals manage to provide the collectively desired good and when do they fail? Neighbourhood support is assumed to emerge as a public good from the individual contributions made by members of the local neighbourhood groups on spatial extents of the environment (*Emergence*).

The behavioural target variable of an agent is the individual contribution to neighbourhood support in the next time step of the model. Possible interference with the generally multi-facetted decision-making in contexts other that the public good provision is not considered.

Deliberative decision-making is modelled by an implementation of HAPPenInGS: Investment options are evaluated with respect to the subjective preferences of an agent (*Objectives*) yielding an expectation of the subjective utility associated with executing the behaviour (*Prediction*). The selection of a behaviour is based on the comparison of the expected utilities associated with the behavioural options at an agent's disposal (*Adaptation*).

Learning is modelled by allowing agents to collect experiences about the outcomes of deliberative decision-making over time. Agents memorise past outcomes of their selected behaviours along with the situational context, i.e. the weather condition in which it was selected. Behaviours that were repeatedly confirmed by deliberation (see above) become an agent's "habit" for that specific situation, i.e. during agent decision-making the behaviour is directly selected without going through the process of deliberation.

Deliberative and habit-based decision-making is complemented by explorative decision-making where with a fixed low probability an agent "explores" by selecting a behavioural option at random.

Agents can perceive the behaviour of other agents in their group and the behaviour of neighbouring agents in their social network (*Sensing*). Furthermore, agents perceive the level of the public good provided by their group, the global weather condition, and the information campaign for their respective neighbourhood group (*Sensing*). These perceptions are used in the utility calculation according to HAPPenInGS. Apart from these perceptions agents do not interact with each other (*Interaction*).

Stochastic processes are involved during the initialisation when assigning agents their spatial positions in the non-social environment and when setting up the social network (*Stochasticity*). Furthermore, decision-making has pseudo-random components: During deliberation, behavioural options are selected with a probability reflecting their expected utility. During exploration a behavioural option is selected at random where each behaviour has the same probability of being selected (*Stochasticity*).

Agent *collectives* are implied by the position of individual agents in the non-social environment. Agents located in the same neighbourhood belong to an agent group that collectively provides a local public good on the spatial extent of the neighbourhood.

The main outputs of the model are based on observed investments behaviours of individual agents and on the level of the public goods provided by the agent groups. Further performance indicators are introduced in section 4.5.1 (*Observation*).

4.4.5 Initialisation

This section reports on how the socio-empirical dataset described in section 4.4.6.2 is used to setup a representative agent population for the target region. The rationale of agent initialisation is (a) to represent lifestyles as agent types, (b) to define neighbourhood groups as agent groups that reflect the lifestyle composition, size and spatial location of the respective market cell, and (c) to define a directed social network that reflects spatial closeness of the agents and the milieu properties of their agent type.

4.4.5.1 Lifestyles as Agent Types

To setup agent types for the respective lifestyles we define different agent preference sets as introduced in section 4.4.7.2. The preference sets used for the simulations are displayed in Table 6. The preference values are based on expert ratings by researchers applying Sinus Milieus® in empirical and modelling contexts, on lifestyle documentations by Sinus (Sinus Sociovision, 2007) and on results of a sensitivity analysis of the model (see section 3.3).

Lifestyle	Preference set			
	publicGood-Importance	*egoisticTendency*	*altruisticTendency*	*socialConformity-Importance*
Leading	1.0	0.1	0.3	0.15
Traditional	1.0	0.1	0.3	0.3
Mainstream	1.0	0.2	0.2	0.3
Hedonistic	1.0	0.3	0.1	0.15

Table 6. Lifestyles and agent preference sets. See text for further explanations.

Agent preferences reflect that traditional and leading lifestyles exhibit rather altruistic behaviour while hedonistic lifestyles are more egoistic and mainstream are somewhat undecided (neutral). Traditional and mainstream lifestyles desire to behave in a way that conforms to the behaviour shown by their social peers, whereas leading and hedonistic lifestyles decide more independently. Finally, the public good character of the situation is made reference to by assigning all agent types a high preference for working neighbourhood support during heat waves.

4.4.5.2 Neighbourhood Groups

To setup agent groups reflecting the lifestyle composition, size and spatial location found in the Microm® data we construct for each market cell a number of fixed-size agent groups (size 20 is used here) such that the total number of agents reflects the number of households in the market cell (one agent per ten households) and the distribution of agent types fits the lifestyle distribution found in the data for the respective market cell. Furthermore, we place the agents randomly inside their market cell. The resulting population setup thus is empirically founded and provides spatial relationships between agents as well as lifestyle heterogeneity.

4.4.5.3 Social Networks

We initialise a directed social network where a network link from agent A to agent B means that B is influenced by A. In the model, the investment behaviour of A is perceivable by B and contributes to B's evaluation of its social conformity goal along with the behaviours of all other agents having outgoing social network links to B (see section 4.4.7.2).

Social network initialisation is based on the assumption that agents differ in their social network integration depending on their type, i.e. the lifestyle they represent. In empirical social network research the concept of homophily stands for this understanding that individuals strive to shape the composition of their personal networks according to their preferences regarding attributes of their social peers like e.g. gender, religion, or social class (McPherson, Smith-Lovin, & Cook, 2001). However, the formation and maintenance of an individual's social network is subject to external restrictions, i.e. the pool of potential network partners is limited e.g. depending on an individual's daily activities, the composition his urban neighbourhood, or his working environment. Therefore it is common to distinguish between "baseline homophily" reflecting this interplay of personal preferences and local opportunities, and "inbreeding homophily" which reflects the understanding that local restrictions are to some extent overridden by personal preferences (McPherson et al., 2001). These two basic principles are accounted for during the network initialisation.

For the initialisation process we use the matrix displayed in Table 7. The first row holds the desired number of ingoing network links for each agent type. The last four rows define for each agent type the composition of the set of influencing agents by specifying the probabilities that an agent of type X has an ingoing link from an agent of type Y. For example the second last row of Table 7 reflects that agents representing mainstream lifestyles have ingoing links from agents representing leading lifestyles with probability 0.6 whereas links from agents of type traditional have a probability of 0.1. In essence, for each agent type, the matrix holds information about the preferred size and composition of its personal social network.

		Lifestyle			
		Leading	Traditional	Mainstream	Hedonistic
Desired in-degree		15	5	5	10
Rewiring Probability		0.2	0.05	0.1	0.2
Probability to link to:	Leading	0.8	0.6	0.6	0.5
	Traditional	0.0	0.3	0.1	0.0
	Mainstream	0.0	0.1	0.3	0.0
	Hedonistic	0.2	0.0	0.0	0.5

Table 7. Expert rating of lifestyle network preferences. Whereas members of leading and hedonistic lifestyles have far reaching networks and thus are assigned a high rewiring probability, people of traditional lifestyles do not. Data is based on Schwarz (2007). Table was adapted from Holzhauer, Krebs, and Ernst (2011)

One of the basic sources of baseline homophily is the geographical space individuals are embedded into. In order to reflect the characteristics of the spatial composition in the network initialisation, we define opportunity sets as the sets of agents located within a certain radius around a focal agent A. Depending on the type of an agent B from A's opportunity set we construct a network link from B to A with the type specific probabilities shown in Table 7. This process is repeated for all agents from the opportunity set. The opportunity set is stepwise extended up to a maximum radius (depending on the local population density) or until the maximum in-degree of the focal agent is reached. Then, in order to account for inbreeding homophily, network links are rewired with the type specific probabilities specified in the second row of Table 7. For this global rewiring process the opportunity set is extended to the complete agent population, i.e. rewiring introduces some long-distance links that are unbiased by local restrictions.

For further details of the described process of spatial and social network initialisation, refer to Holzhauer, Krebs, and Ernst (2011, 2012).

4.4.6 Input Data

This section reports on the external data drivers of the model namely the climate scenario that provides agents with a perception of weather conditions in a daily resolution and the socio-empirical dataset that is used for agent initialisation. An overview of the datasets was given previously (Krebs et al., 2011). Here, we extend especially the description of the socio-empirical dataset.

4.4.6.1 Climate and Weather

The weather data driver is based on a climate projection generated by the regional climate model CLM (Climate Local Model; Hollweg et al., 2008) based on the scenario A1B of the IPCC (Intergovernmental Panel on Climate Change). In contrast to statistical models CLM is dynamic in that it allows for the emergence of entirely new weather conditions compared to historical weather data. For this reason and others all projects in the KLIMZUG-Northern Hesse network use the CLM data as a climate reference (Matovelle, Simon, & Rötzel, 2009b, Matovelle, Simon, & Rötzel, 2009a).

The full dataset comprises air temperature, wind speed, rainfall, snowfall, and cloud cover with a temporal resolution of 1 or 3 hours. We use the air temperature data stream to obtain daily maximum temperatures for the investigated region. Figure 20 shows the predicted maximum daily air temperatures as spatial means for the entire region. Heat days with a maximum air temperature of 30° are marked in red; numbers quantify the count of heat days in one year. We observe a high variability in the numbers of heat days per year as well as the fact that heat days are only expected from May to September.

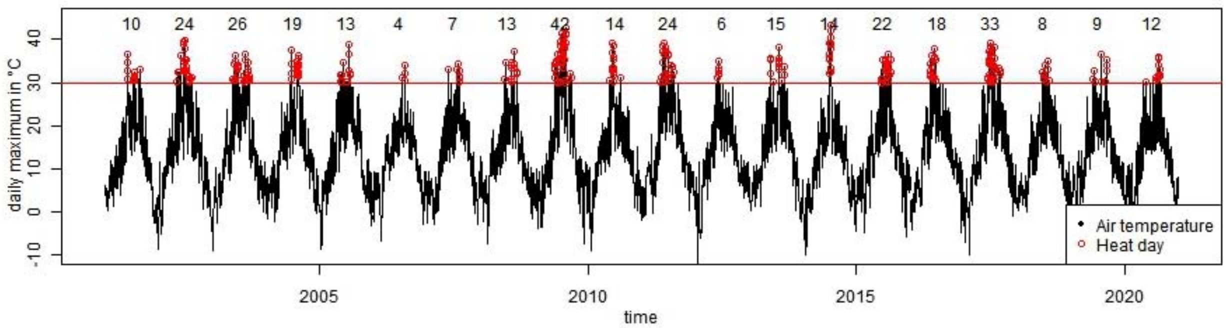


Figure 20. Weather sequence for the target region and the selected climate scenario in daily resolution Source: Krebs, Holzhauer, and Ernst (2011).

4.4.6.2 Spatially Referenced Socio Demographic Data

The described climate data mainly reflects the physical context in which agents make their decisions in the model. Data may straight forward be integrated in an ABSS by allowing agents to perceive temporally varying weather conditions which in turn allows them to assess the effective importance of neighbourhood support at any given point in time. It is far more challenging to initialise the agent population in way that it reasonably reflects the social situation characteristics found in the target area. A possible approach to structuring the target population is the concept of sociological lifestyles (Bourdieu, 1984) that clusters individuals typically in relation to their attitudes, values and orientations.

We apply the Sinus-Milieus® (Sinus Sociovision, 2007) that are commonly used in commercial market research, but also in environmental research (Gröger, 2011; Schwarz & Ernst, 2009). Sinus-Milieus® group individuals or households along the classical dimension of social status given by income and education, and supplement this grouping by a second dimension that reflects social value orientations like tradition, modernisation and re-orientation. Figure 21 displays the classification of the ten Sinus-Milieus® for Germany: Establisheds are self-confident and think in terms of success and feasibility, while Modern Performers are the young and unconventional elite. Postmaterialists have liberal and postmaterial values, intellectual interests. The old German educated class finds itself in the Sinus-Milieu® Conservatives with humanistic values and cultivated forms. Traditionals prefer security and orderliness, while GDR-Nostalgia believe in socialist visions of solidarity and justice. The modern mainstream aims at professional and social establishment and is very status-oriented, while consumption-materialists feel socially discriminated and aspire to the consumption patterns of the Mainstream. Experimentalists are very individualistic and see themselves as lifestyle avant-garde. Pleasure seekers have a low social status and refuse to accept the expectations of a performance-oriented society.

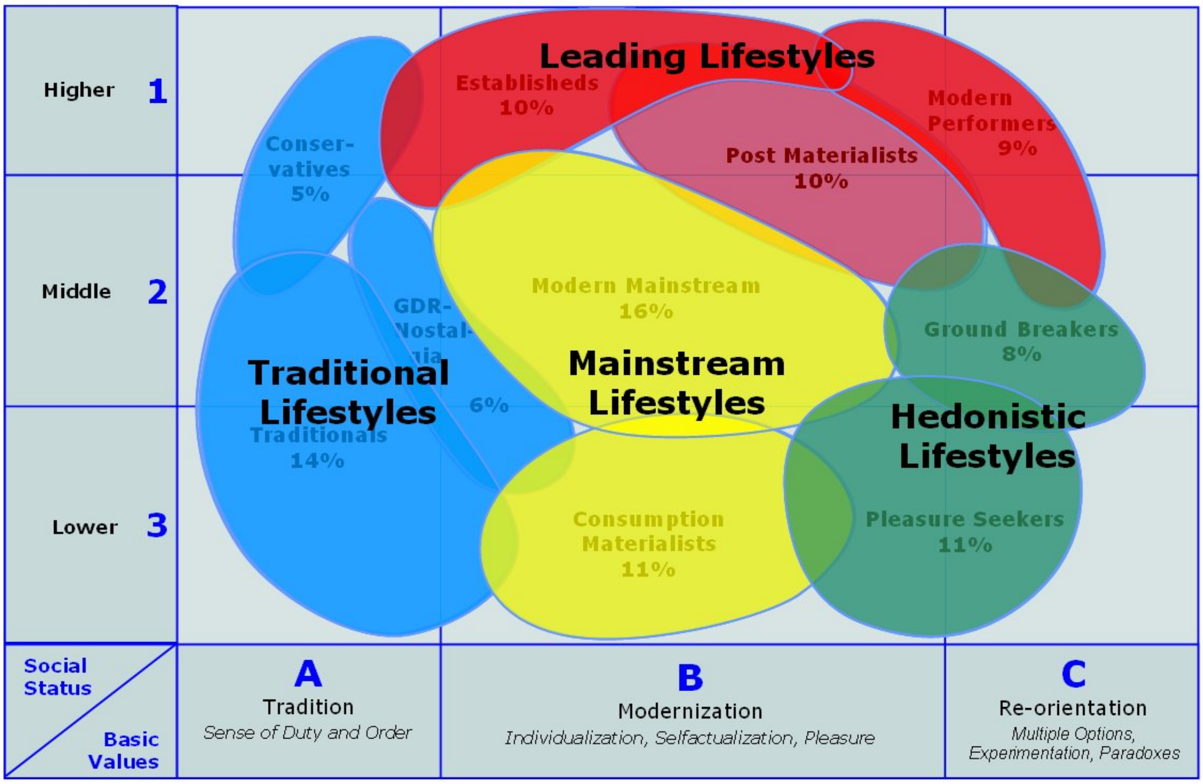


Figure 21. The ten Sinus-Milieus® for Germany and their aggregation to four milieu groups. Milieus located in the upper region of the diagram are characterised by higher levels of education, more income and belong to upper occupational groups. From left to right milieus increase in their degree of modernisation and individual innovativeness. Source: Sinus Sociovision (2007) adapted.

Figure 21 also shows that there are smooth transitions between the individual milieus. Therefore, in order to stress distinctions between milieus it is common to cluster the ten Sinus-Milieus® into four different milieu groups (Gröger, 2011; Schwarz & Ernst, 2009) as displayed in Fig. 3: leading lifestyles, mainstream lifestyles, traditional lifestyles, and hedonistic lifestyles. Additionally, for the context of neighbourhood support we expect only minor differences between milieus within one group especially when used in an ABM.

To make the Sinus-Milieus® usable in a spatial context Sinus Sociovision and Microm® (Micromarketing Systeme und Consult GmbH - Microm Consumer Marketing http://www.microm-online.de) merged the Sinus-Milieus® with the MOSAIC database. MOSAIC is a geodemographic segmentation system, i.e. a multivariate statistical classification technique for inferring if the individuals of a population fall into different groups by making quantitative comparisons of multiple characteristics. The basic assumption is that the differences within any spatial neighbourhood should be less than the differences between neighbourhood groups.

The merged dataset of spatially referenced socio demographic data for 2007 and temporal extrapolations until 2030 is available to the project. For the target region, the extrapolations do not show dynamics that can be expected to have major influence in the context of neighbourhood support. Therefore, we use the 2007 empirical data as the socio-empirical base for the results presented in this paper. The geographical reference units are so-called market cells that comprise several hundred households. For each of the market cells the dataset provides the number of households belonging to each of ten different Sinus-Milieus®. Again, for the use in the model we cluster data obtaining four milieu groups. In the following we refer to milieu groups simply as lifestyles.

4.4.7 Submodels

4.4.7.1 Environmental context: Algorithmic representation of neighbourhood support as a public good

The representation of neighbourhood support corresponds to the abstract definition given in the ODD description of HAPPenInGS-A (see section 3.2.7.1). In order to provide a closed ODD description of HAPPenInGS-N we briefly summarise the core elements and state the parameter settings used.

Each local neighbourhood group has n members and group size remains constant over time. The success of neighbourhood support is calculated from the contributions of the members of the providing group. An agent's contribution is represented as a real number x ($0 \leq x \leq 1.0$) where x is one of 11 distinct behavioural options that reflect investments of 0.0, 0.1 up to 1.0 in steps of 0.1. Based on the contributions of the n agents we determine the level of the generated public good following Equation 1. Refer to Figure 6 for the curve for n=20, γ=5, and m=7, which is used in the simulations. Substantial neighbourhood support is generated for individual investments above 0.15 (i.e. for a group of 20 above a group investment of 3.0 units). The success of support approaches 100% if the mean of individual contribution reaches at least 0.4 (group investment of 8.0 units in a group of 20).

4.4.7.2 Agent decision-making

In HAPPenInGS-N, agent decision-making is based on concepts of the LARA framework (Lightweight Architecture for boundedly Rational Agents, Briegel et al., 2012). LARA enables handling large numbers of heterogeneous agents (up to hundreds of thousands) and their decision processes in a way that is well embedded in existing psychological theory on human decision-making. The purpose of LARA is to provide policy simulation with a credible modelling of actors and citizens in particular. In line with Briegel et al. (2012) we distinguish different types of decision-making that humans adopt depending on the demands of a particular situation. In HAPPenInGS-N three types of decision-making are considered: deliberative decision-making grounded in the HAPPenInGS theory, exploration, and habit-based decision-making.

The remainder of this section describes the implementation details of the three modes of decision-making and their respective triggering during agent decision-making.

4.4.7.2.1 Deliberation and exploration

In HAPPenInGS-N the implementation of deliberative decision-making and exploration mainly corresponds to the respective description given in the submodels-section of the ODD description of HAPPenInGS-A (see section 3.2.7.2). To provide a complete ODD description of HAPPenInGS-N we summarise the respective section here.

In deliberative agent decision-making an agent's selection of a behavioural option is guided by the preferences stated by the HAPPenInGS theory (see Table 2). The knowledge of agent about the effectiveness of its behavioural options is represented by a utility calculation which relates the perceptions of an agent and its expectations about the outcome of executing a behaviour to the agent's subjective preferences.

To assess the subjective utility of its behavioural options, each agent perceives the present success of neighbourhood support provided by its respective group, and supposes that the n-1 other agents of its group keep to their previous investment decisions in the next time step. Then, each agent forms an expectation of the success of neighbourhood support associated with each of its possible next investment decisions. Next, an agent perceives the average level of contributions within its group and the average level of contributions by its social network peers and determines the expected utility of each investment option x regarding its subjective preferences (see Table 2). The formula used to calculate the expected utility u of an investment option x is displayed in Equation 2. For deliberative decision-making, the final selection of an investment option is represented by a probabilistic choice model based on the expected utilities (see Equation 3).

Like in HAPPenInGS-A, deliberation is complemented by exploration which is modelled by having agents select a random investment level (uniformly distributed).

4.4.7.2.2 Habits

Habit based decision-making reflects the understanding that most of the individual daily activities are routine behaviours that do not involve deliberation. Nevertheless, psychological research shows that such habits (Triandis, 1980) are to be understood as condensed representations of past results of deliberative decisions that become activated in certain situational contexts as an "automaticity" (Aarts & Dijksterhuis, 2000). Therefore, in HAPPenInGS-N, habits are grounded in the HAPPenInGS theory that describes the adaptive behaviour which forms the basis of the involved processes of learning.

We model habits and their formation as a process of Learning by Doing (Anzai & Simon, 1979): Agents build up and use a body of experience over time that allows them to recall behaviours that led to satisfactory outcomes in certain contexts and to distinguish those behaviours from unsuccessful ones. Repeatedly successful behaviours become habits that determine an agent's routine behaviour.

In the ABM literature the underlying model is known as reinforcement learning (Bendor, Mookherjee, & Ray, 2001; Erev & Roth, 1998). Reinforcement learners utilise experience to select (or avoid) behaviours on the basis of recalled consequences. Actions that resulted in satisfactory outcomes in the past are likely to be repeated in the future, whereas choices that led to unsatisfactory experiences are avoided.

While forming their habits agents memorise past outcomes of their selected behaviours. Memory entries are quadruples {S, b, r, u} where:

- S is the he situational context of the decision: What was the weather condition under which the memorised decision was made? Two contexts based on agents' perceptions of the environment are distinguished ("normal weather" and "heat day").
- b is the behavioural option, i.e. the investment level selected in context S.
- r is the reinforcement of b in context S: How often did deliberative decision-making confirm the behaviour in the respective situation?
- u is the time-average subjective utility of b in S: What level of utility was in average achieved by selecting the behavioural option in the situational context?

During deliberative decision-making agents continuously collect experience: Assume, in situational context S* an agent selects behavioural option b* which has a subjective utility u*:

- If the memory does not hold an entry for context S* then create a new entry (S*, b*, 1, u*).
- If b* was selected before in context S* then update the corresponding memory entry by increasing the reinforcement by 1 and adjusting the subjective utility of b* in context S* using u*.
- If for context S* a different behavioural option b** (b*<>b**) is in memory and the memorised utility of b** is lower than the utility of b* then add a new entry {S*, b*, 1, u*}.

If in a given situational context an agent possesses a sufficiently confirmed (high reinforcement, r>=10 is used here) memory entry the recalled behaviour becomes an agent's habit for that specific situation.

4.4.7.2.3 Decision mode selection

Deliberation is used if in a given context there is no useable (confirmed) experience available to an agent, i.e. habitual behaviour is not possible. Furthermore, deliberative decision-making may be triggered by external events like e.g. the perception of an information campaign by an agent that makes it elaborate on its behavioural options despite existing habits. With a probability of 1% agents use exploration instead of deliberation. In all other cases agents use their formed habits.

4.5 Results

Here, we report on simulation results that were published in Krebs, Holzhauer, and Ernst (2013) and that extend early results (Krebs et al., 2011). Simulations cover the city of Kassel represented by a total of more than 9000 agents. In addition, we present scenario assessments based on temporal dynamics, behavioural change within the population and differences between lifestyles, and spatial aggregations allowing identifying hot spot areas with low impact of mobilisation campaigns.

4.5.1 Setup and performance Indicators

Simulations were conducted for the urban region of Kassel that comprises 23 districts characterised by a total of 196 market cells from Microm® data. For the region, agent initialisation results in 459 agent groups of size 20, i.e. 9180 agents in total. Agents are initialised with empty memory structures, i.e. without any pre-initialised habits, and with low initial investment levels (normal distributed). In the simulations, agent decision-making is triggered twice per day. In order to obtain plausible initialisations of agent perceptions, behaviours and memory structures we run the model for 10 years with the described weather sequence from 2001 to 2010. This baseline period is mainly a model warm-up phase that produces a status quo state of the simulation for 2010.

During the period 2011 to 2020 we explore the effects of different intervention scenarios. Here, we focus on interventions in the form of mobilisation campaigns, e.g. the distribution of information material. As stated above we model the individual-level effect of mobilisation by having agents adopt the deliberative mode of decision-making despite possibly existing habits while they perceive an on-going campaign. We compare two different intervention scenarios:

- Full mobilisation: During heat waves, mobilise all neighbourhood groups.
- Success-dependent mobilisation: During heat waves, mobilise only unsuccessful neighbourhood groups.

In all cases interventions start 2013 and run until 2015. Furthermore, the presented results for the intervention scenarios use the same initialisation settings including the random number streams.

Results are reported with respect to four different indicators:

- *investmentHeat*: Agent behaviour during heat waves in terms of the selected investment level at a given point in time.
- *investmentNormal*: Agent behaviour during normal weather conditions in terms of the selected investment levels at a given point in time.
- *neighbourhoodSuccess*: Success of the collective action on the level of neighbourhood groups at a given point in time during a heat wave.
- *interventionPerception*: Agent perception of an intervention, i.e. whether an agent is target an intervention at a given point in time.

The simulation results described in the following section use these indicators on different temporal, social and spatial levels of aggregation.

4.5.2 Result visualisation

We introduce three types of evaluation diagrams that are used for the documentation of the baseline period and the intervention scenarios. The first visualisation (first diagram in the figure sets) focuses on the temporal development of the simulations and uses the following aggregations of the four performance indicators:

- The average investment level during heat waves (shown in red): For each time step, calculate the mean of *investmentHeat* over all agents.
- The average investment level during normal weather conditions (green): For each time step, calculate the mean of *investmentNormal* over all agents.
- The yearly average percentage of successful neighbourhood groups during heat waves (blue): For a given simulation year, calculate the mean of the percentage of neighbourhood groups with *neighbourhoodSuccess*>=0.75 over all time steps belonging to the year.
- The yearly average percentage of intervention coverage (black with bounding vertical dashed lines): For a given simulation year, calculate the mean of the percentage of agents with *interventionPerception*=1 over all time steps belonging to the year.

The second type of diagram draws on the heterogeneity of the simulated agent behaviours during heat waves. We group agents with respect to their average investment level (*investmentHeat*) during the last three years of the considered time range (2008-2010 for baseline period and 2018-2020 for intervention scenarios) and with respect to their milieu group. For the investments we use four categories. Results are displayed as stacked bar charts. The diagram is mainly used to assess the baseline on the level of individual behaviours and the impact of interventions on behaviours.

The third visualisation shows the simulated spatial distribution of neighbourhood support. Here, we cluster neighbourhood groups according to their average success in providing support (*neighbourhoodSuccess*) during the last three years of the respective time range. Then, we aggregate the data spatially on the level of 48 statistical units used by the city administration as sub-division of the city districts. Generally, population density differs between statistical units. Therefore, we show a circle with diameter proportional to the number of simulated neighbourhood groups within the respective statistical unit (scaled linearly from 1 to 26). This diagram type is e.g. used to identify spatial hot spots with low potential for social mobilisation.

4.5.3 Baseline period

The temporal development during the baseline period from 2001 to 2010 is displayed in Figure 22. We observe an initially high volatility of investment behaviour (green and red). During normal weather average investment quickly converges to low levels (green, still above 0). By 2010 average investment levels during heat waves (red) stabilise to 0.08. In addition, approximately 10% of the neighbourhood groups (blue) manage to successfully provide neighbourhood support during heat waves. Correspondingly, Figure 23 shows that a big majority of agents is in the lowest investment category. Furthermore, hedonistic milieus dominate the lowest category while the highest category is only composed of agents belonging to leading and traditional milieus. Finally, Figure 24 shows that rather successful neighbourhood groups are located further west while unsuccessful neighbourhoods are expected to be located in the downtown area close to the geographical centre of the map and east from the centre.

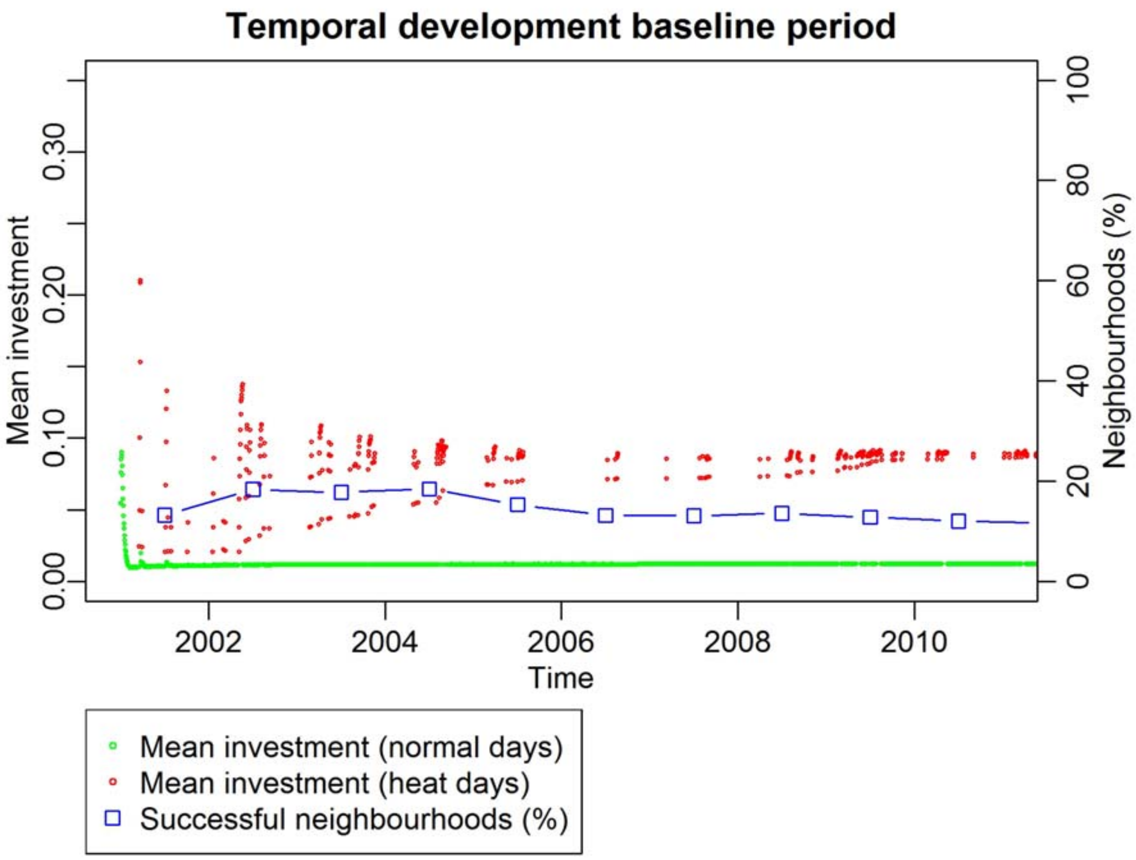


Figure 22. Simulation results for the baseline period. The diagram shows the temporal development during the first 10 simulation years (months May to September): agent behaviours during normal weather (green) and heat waves (red) and the yearly average percentage of successful groups (blue). Adapted from Krebs, Holzhauer, and Ernst (2013).

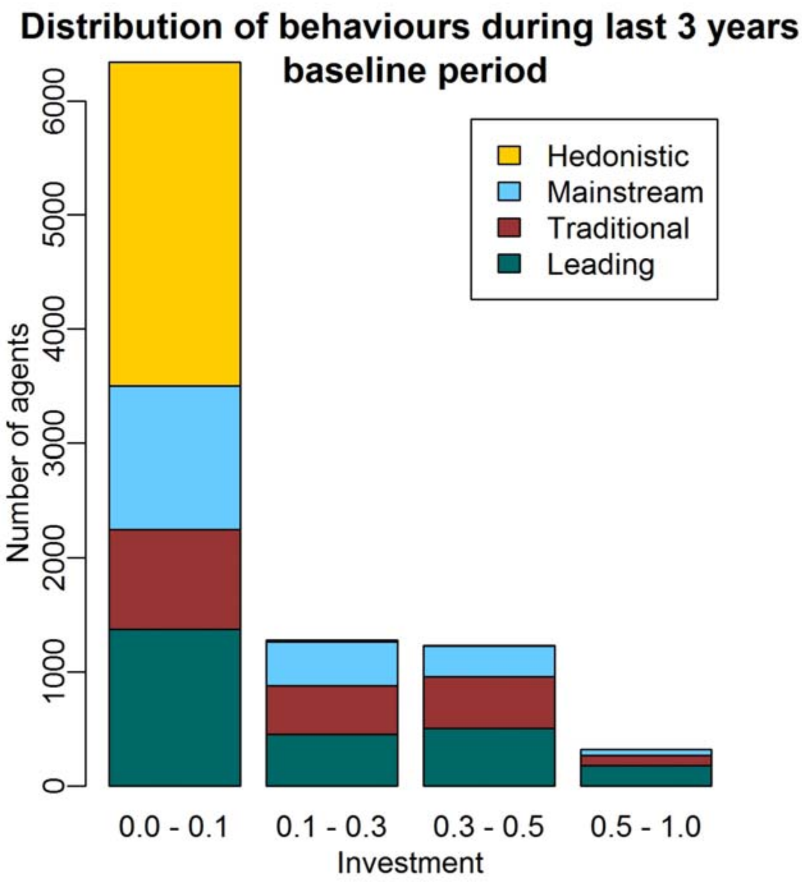


Figure 23. Simulation results for the baseline period. The diagram shows the distribution of behaviours between milieu groups for 2008 to 2010. Adapted from Krebs, Holzhauer, and Ernst (2012).

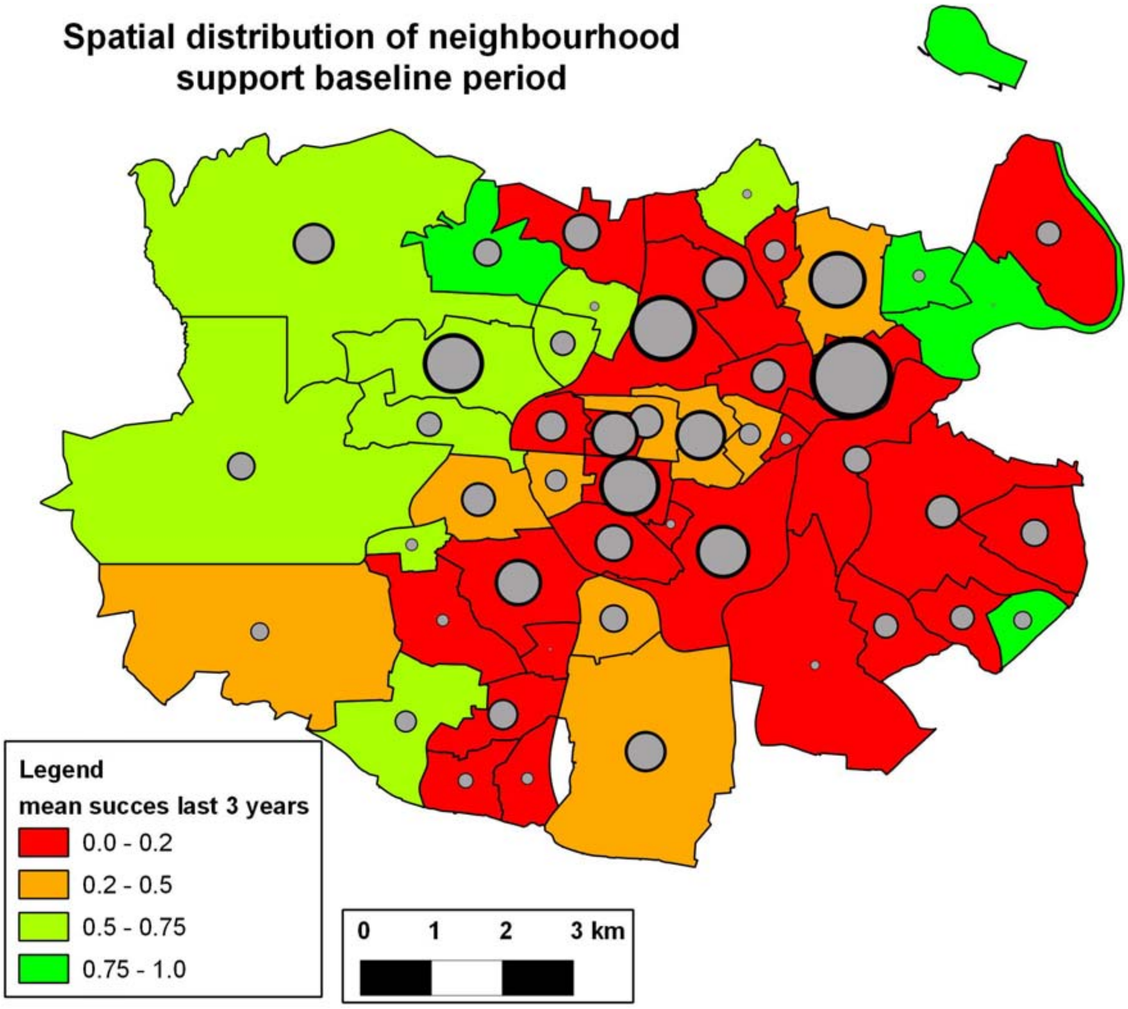


Figure 24. Simulation results for the baseline period. The map illustrates the spatial distribution of neighbourhood support. Data is spatially aggregated on the level of statistical units: Colours show the average success of neighbourhoods during 2008 to 2010. The size of the circles scales linearly with the number of agents located in the statistical unit. Adapted from Krebs, Holzhauer, and Ernst (2013).

For the baseline period, model behaviour plausibly reflects expectations on the level of macro indicators. We see a clear differentiation of agent behaviour between the two weather situations. Furthermore, during heat waves we observe a slow convergence of investment levels which indicates an on-going intra-group coordination processes on the micro level. Likewise, the spatial and socio-behavioural results reasonably reflect the local conditions of the target area.

4.5.4 Scenario 1: Full mobilisation

The following figures illustrate the effect of the modelled full mobilisation campaign. Figure 25 shows the temporal dynamics during the second decade of the simulation after the baseline period. During the campaign (between the dashed black lines) we observe a stressed phase of behavioural volatility followed by a transition to a state where average investments during heat waves are increased and the percentage of successful neighbourhood groups improves to slightly below 50% towards 2020. Again, behaviours stabilise after the mobilisation as they become habitual on the individual agent level. The behavioural impact of the campaign may be evaluated when comparing Figure 26 and Figure 23: Clearly, the third investment category shows the highest increase. Furthermore, the campaign has significant impact on the behaviours of all milieu groups except for hedonistic. Nevertheless, a small number of hedonistic agents changes behaviour – a behaviour that may only be attributed to social network / peer pressure that overrides egoistic social preferences of hedonistic milieus. Similarly, agents belonging to mainstream milieus follow leading milieus in their behaviour and are well represented in middle two investment categories. Figure 27 allows identifying basically three different spatial zones with regard to neighbourhood support: A zone of high success may be observed in the western areas and in the outskirts to the east. A second zone of medium success is located towards the centre and east from the centre. In this densely populated area we suspect a high local variability in support success between the respective neighbourhood groups. Finally, a third zone of very low success may be identified north-east from the centre. In this area the mobilisation is expected to have negligible effect on behaviours.

In summary, three conclusions may be drawn from scenario 1:

- Mobilisation may achieve a phase transition in behaviours and establish new habits that contribute to a better provision of neighbourhood support.
- Mobilisation has major positive impact on the behaviour of leading, traditional and mainstream agents. But, as long as mobilisation targets on changing habits by making agents simply “reconsider” their behaviour, the majority of the hedonistic agent group will remain passive. Due to their substantial proportion of the population they inhibit comprehensive success of the mobilisation.

- Spatially, we can identify a small hot spot area where the campaign has virtually no effect on behaviours and thus either an additional type intervention or focused care-taking activities by public health service seems to be indicated.

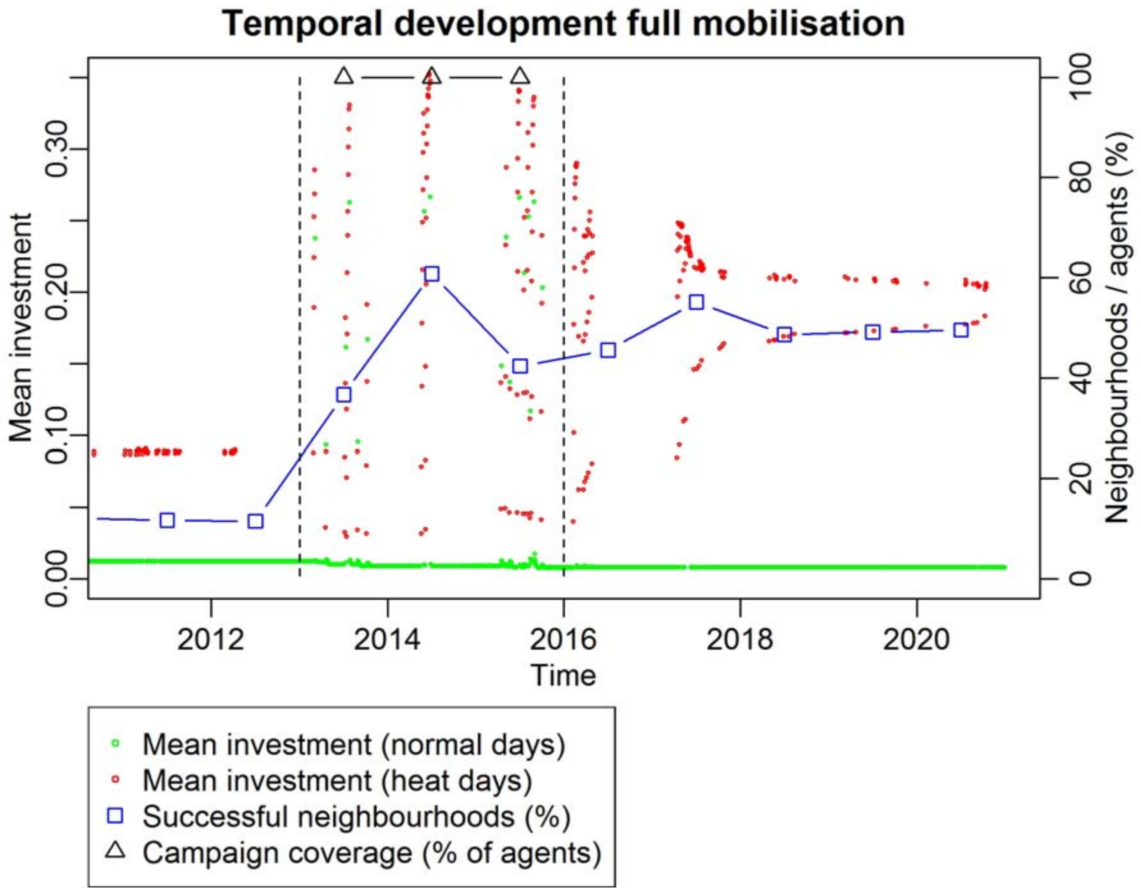


Figure 25. Simulation results for full mobilisation. The diagram shows the temporal development during the 10 simulation years after the baseline: agent behaviours during normal weather (green) and heat waves (red), the yearly average percentage of successful groups (blue) and the percentage of agents target of the intervention (black). Adapted from Krebs, Holzhauer, and Ernst (2013).

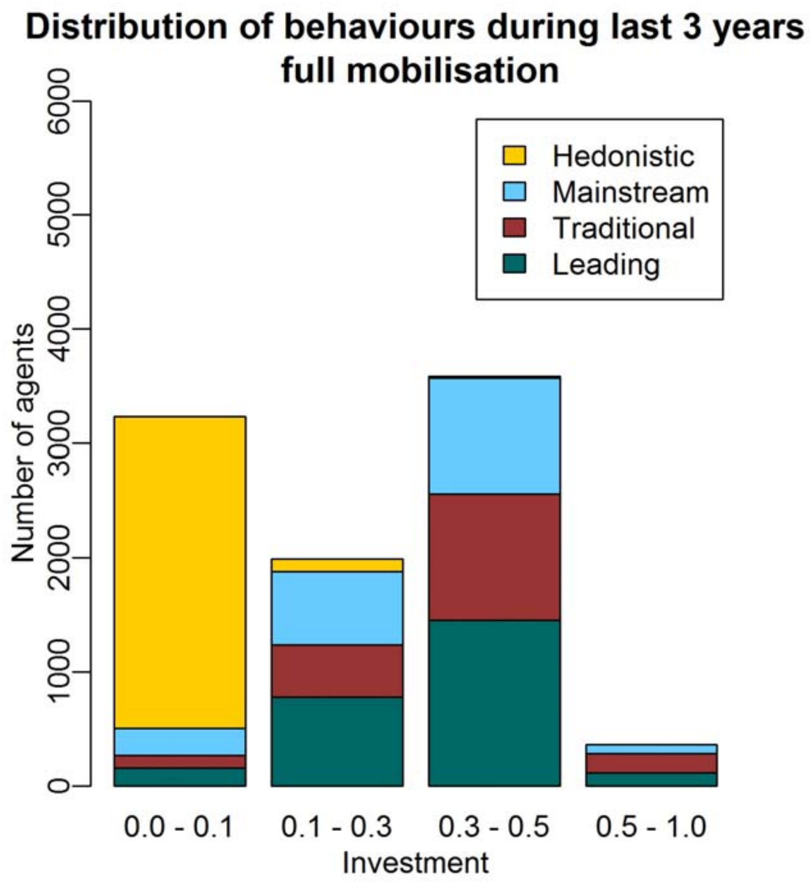


Figure 26. Simulation results for full mobilisation. The diagram shows the distribution of behaviours between milieu groups for 2018 to 2020. Adapted from Krebs, Holzhauer, and Ernst (2013).

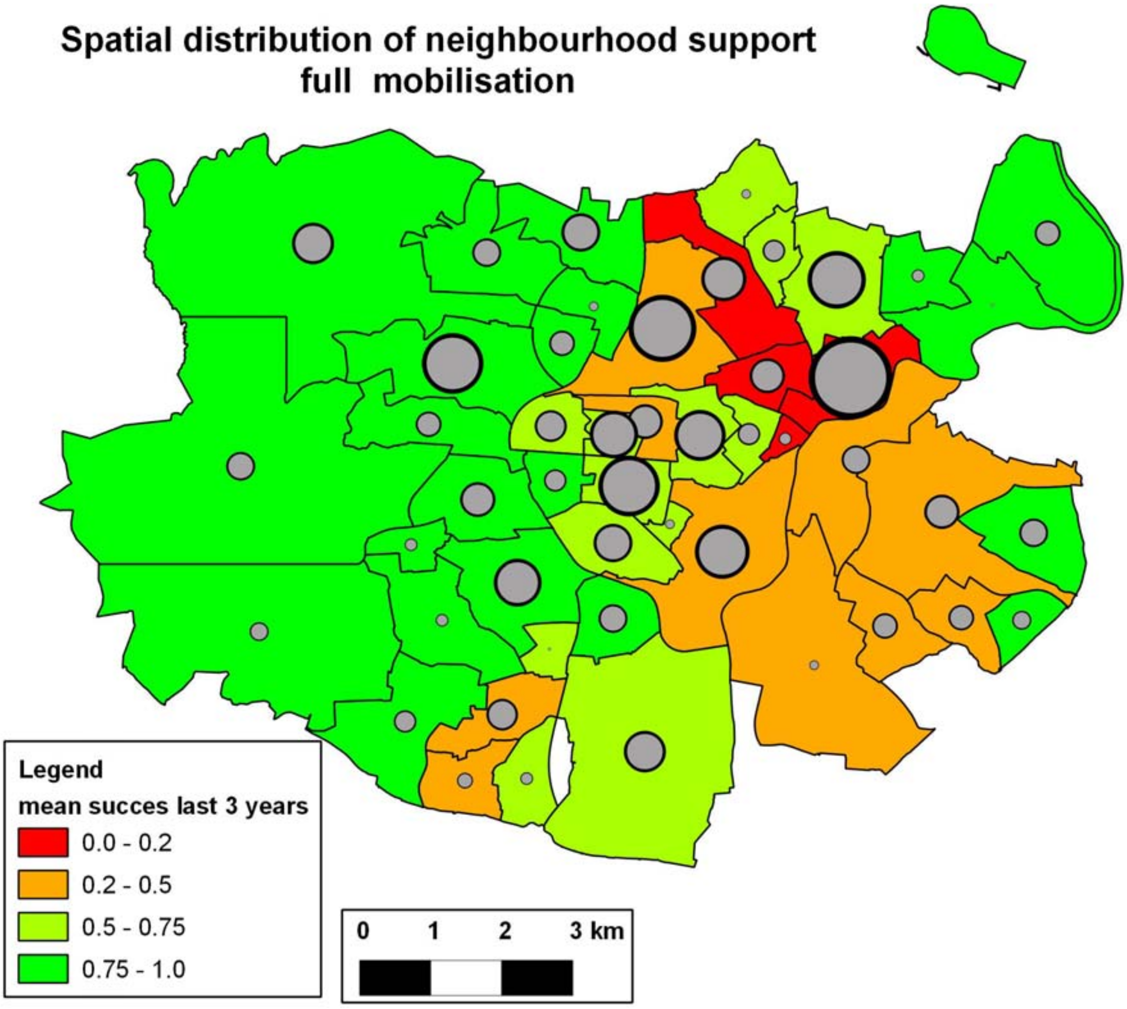


Figure 27. Simulation results for full mobilisation. The map illustrates the spatial distribution of neighbourhood support. Data is spatially aggregated on the level of statistical units: Colours show the average success of neighbourhoods during 2018 to 2020. The size of the circles scales linearly with the number of agents located in the statistical unit. Adapted from Krebs, Holzhauer, and Ernst (2013).

4.5.5 Scenario 2: Success-dependent mobilisation

Simulation results for the success-dependent mobilisation intervention are shown in the following figures (scenarios only differ from 2013 when the intervention is triggered). In Figure 28, qualitatively similar to scenario 1, we observe a phase of volatility on the level of behaviours during the campaign and a quick increase of the percentage of successful neighbourhood groups. In contrast to scenario 1 the percentage of successful neighbourhoods rises to a higher level of around 60%. Furthermore, the magnitude of the volatility phase is much less stressed during success-dependent mobilisation in scenario 2. As a consequence investment levels more rapidly stabilise after the campaign which may be seen when comparing the last 5 years of the two scenarios. In addition, the coverage of the campaign is in average around 40% during the campaign, i.e. instead of targeting the full population like in scenario 1, scenario 2 only requires reaching less than half of the population. Despite this fact, the distribution of behaviours in Figure 29 shows only slight differences to Figure 26: A small decrease in the lowest investment category and small increases in categories 2 and 4. Remarkably, the spatial distribution of neighbourhood support in Figure 30 shows a significant number of areas with increased success compared to scenario 1. Still, the identified hot spot area remains stable.

Summing up, the conclusions drawn from scenario 1 equally hold for scenario 2. The additional insight gained from scenario 2 is that

- a focused campaign that only targets unsuccessful neighbourhood groups has most likely higher impact than the comprehensive campaign in scenario 1.

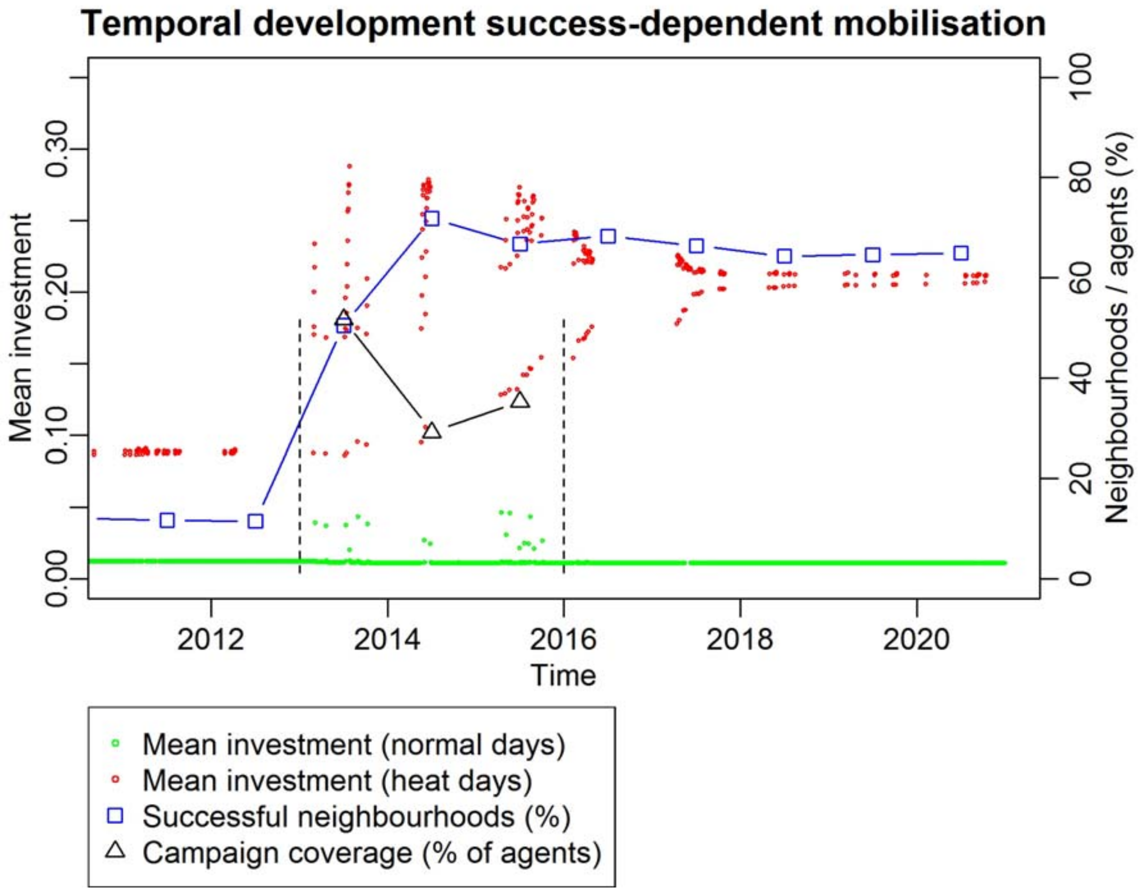


Figure 28. Simulation results for success-dependent mobilisation. The diagram shows the temporal development during the 10 simulation years after the baseline: agent behaviours during normal weather (green) and heat waves (red), the yearly average percentage of successful groups (blue) and the percentage of agents target of the intervention (black). Adapted from Krebs, Holzhauer, and Ernst (2013).

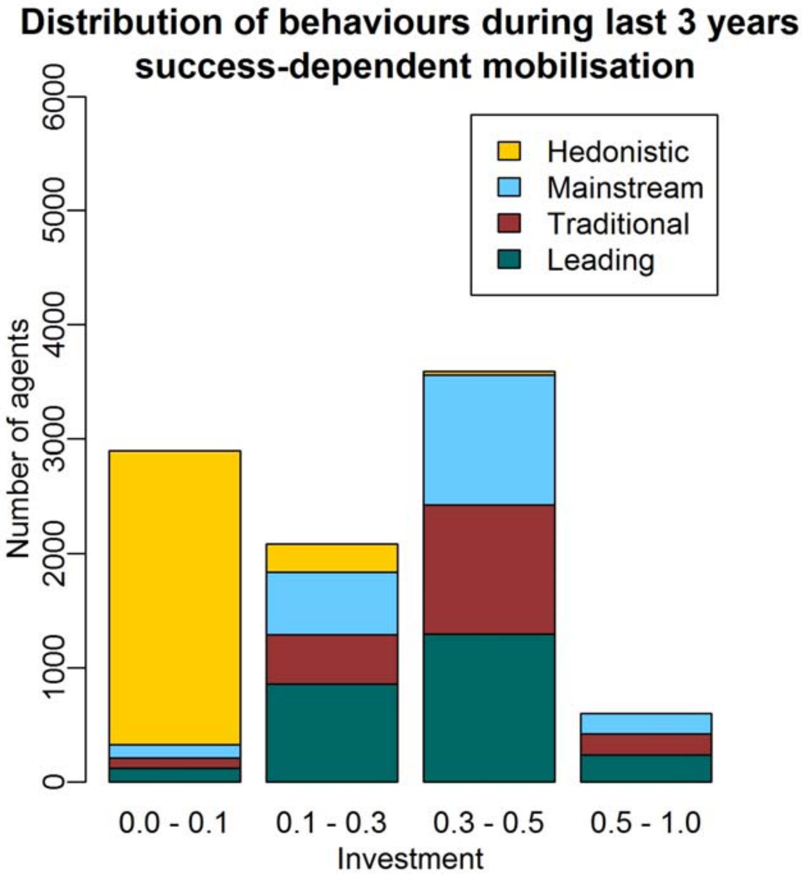


Figure 29. Simulation results for success-dependent mobilisation. The diagram shows the distribution of behaviours between milieu groups for 2018 to 2020. Adapted from Krebs, Holzhauer, and Ernst (2013).

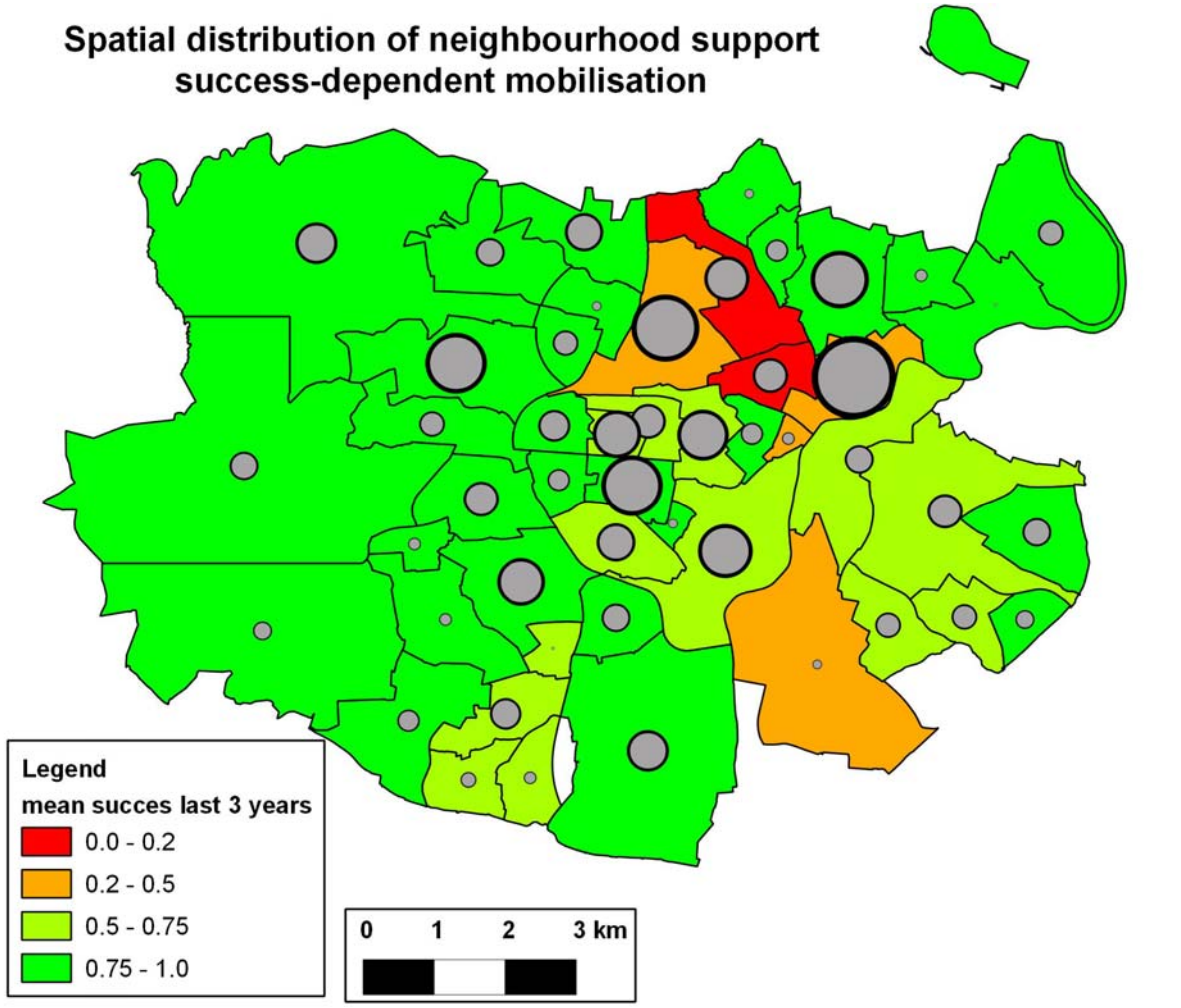


Figure 30. Simulation results for success-dependent mobilisation. The map illustrates the spatial distribution of neighbourhood support. Data is spatially aggregated on the level of statistical units: Colours show the average success of neighbourhoods during 2018 to 2020. The size of the circles scales linearly with the number of agents located in the statistical unit. Adapted from Krebs, Holzhauer, and Ernst (2013).

4.5.6 Comparative scenario assessment

Agent-based simulations commonly show some degree of path dependency conditional to pseudo-random processes included in model initialisation as well as simulation. While the three simulation runs discussed in the previous sections are based on one such initialisation (technically speaking one specific seed for the involved random number generator), this section reports aggregated results obtained from a total of five independent experiments. Accordingly, the results presented here are based on five independent realisations of each the baseline and the two intervention scenarios, i.e. a total of 15 simulation runs. When discussing results we will refer to the respective mean values of the performance indicators and their standard deviation over the five respective experiments.

We compare runs with respect to three different dimensions:

- The extensiveness of the intervention in terms of the percentage of the agent population that has to be reached by the campaign.
- The effect of mobilisation on agent behaviours in terms of the percentage of agents contributing to neighbourhood support.
- The success of neighbourhood support in terms of percentage of neighbourhood groups successfully providing support.

The mean values of the indicators and standard deviations in parentheses are shown in Table 8.

#		Baseline Period	Full Mobilisation	Success-Dependent Mobilisation
1	Percentage of agents that are target of an intervention	**0** (SD=0.0)	**100** (SD=0.0)	**39** (SD=2.2)
2	Percentage of agents contributing to neighbourhood support	**32** (SD=2.3)	**65** (SD=0.3)	**68** (SD=0.5)
3	Percentage of successful neighbourhood groups	**14** (SD=2.1)	**52** (SD=1.8)	**62** (SD=1.6)

Table 8. Comparative scenario assessment. We show mean values over the last three years of the respective time range. Indicator 1 quantifies the coverage of an intervention, indicator 2 shows the proportion of agents with an investment of at least 0.1, and indicator 3 shows how many neighbourhood groups achieve a support success of at least 0.75. The values are means over five independent simulation runs and the respective standard deviations are displayed in parentheses.

Clearly, success-dependent mobilisation is most efficient when relating the effort that has to be put in the intervention to the achieved effect in terms of behavioural change and provision of neighbourhood support. Remarkably, the percentage of agents with non-zero investments increases only by 3% when comparing the two interventions while the resulting success of neighbourhood support rises by 10%. Apparently, the more targeted campaign manages to selectively push mobilisation in agent groups that were initially close to being successful.

4.6 Discussion and conclusions

The presented work examined the individual behavioural perspective of climate change adaptation. One topic in this context concerns local mobilisation of neighbourhood support during more frequent heat waves under conditions of climate change.

Starting out from an agent population that is initialised by large scale socio-empirical data on the micro-level we have investigated how mobilisation campaigns take effect in terms of macro-level indicators. Despite targeting at population sizes that are usually the domain of micro simulation the presented model is built on assumptions that are well grounded in psychological theory: The modelled citizen agents decide by deliberation based on the HAPPenInGS theory, by following habits based on collected experience, or by simple exploration. Furthermore, agents are socially embedded in large scale social networks that reflect inter-agent homophily and spatial closeness.

The model allowed us to observe how intervention campaigns help to break prevailing habits in a population and establish new behavioural patterns that persist after the end of the intervention. Furthermore, the descriptive richness of the model enabled a socio-behavioural impact assessment of the interventions. We could demonstrate that agents representing leading, traditional and mainstream lifestyles are sensitive to mobilisation and change behaviour whereas hedonistic lifestyles are rarely reached by the considered types of intervention. A spatial analysis allowed identifying city regions with substantial potential for neighbourhood support and a small region where even comprehensive information campaigns show insignificant effect. Finally, we could show that comprehensive intervention campaigns that draw on the mobilisation of the full target population may be less successful that more focused campaigns that only mobilise population groups that fail to provide neighbourhood support.

Simulation results suggest that a selective intervention is most effective from the perspective of policy makers when relating the required mobilisation coverage to the achieved effect. However, the modelled selective mobilisation is quite strict in assuming that unsuccessful neighbourhood groups may be identified dynamically at any point in time and accessed by a campaign. In order to define and model practically feasible selective interventions further research on the application domain is required. The focus of further research will be on alternative intervention scenarios like spatially selective mobilisation based on the results of the baseline simulation or on lifestyle specific interventions that draw on the fact that lifestyles differ in their communication channels. Furthermore, there is some empirical evidence that especially hedonistic lifestyles react more sensitively to material incentives (like voucher booklets) that reward contributing to neighbourhood support.

A more general point has to be made on model validation. In the given domain there are no empirical datasets suitable for macro-level validation. We rather have to rely on domain experts to confirm that simulation results reasonably reflect the situation characteristics in the target area. Nevertheless, the utilised detailed socio-demographic initialisation data ensure a high level of micro level validity. We plan to further increase this empirical founding by including results of on-going surveys of the target area. Finally, it has to be remarked that the model does not consider higher order dynamics like the emergence of new lifestyles over time, because there is no usable empirical evidence on such dynamics and because it is beyond the scope of the presented model. Still, it is safe to assume that such lifestyle dynamics are no major driver during the modelled time period.

5 Modelling land reclamation in the Odra river catchment

The empirical background of this chapter is provided by a case study of the Odra valley in Poland close to the border to Germany. We report on an ABSS with a coupled hydro-agricultural model that simulates the collective decision making of typical landowners in the Odra River catchment under fluctuating socio-environmental boundary conditions. Farmers in the region are caught in a social dilemma: While, in principle, the existing land reclamation system (LRS) of ditches and canals can absorb the negative effects of extreme weather conditions, its proper functioning requires collective action as regards maintenance. However, such a collective effort is undermined by a number of structural properties of the dilemma situation including the generally asymmetrical dependencies between farmers resulting from the different locations of their land parcels along the LRS, the activity of initiator persons promoting the LRS, or compensatory payments to farmers suffering from crop losses. In the model farmers decide whether to maintain their local section of the LRS or not based on their economic success and the social support they receive from acquaintances and initiators. We present simulation results that explore the impact of different intervention scenarios on social mobilisation.

The work presented in this chapter was conducted during the CAVES[3] project (Complexity: Agents, Volatility, Evidence, and Scale; duration from 2005 to 2008). Simulation results were previously published in Krebs, Elbers, and Ernst (2008); Krebs, Elbers, and Ernst (2007); Krebs & Ernst (2008). We will show that the presented research is linked to the theory framework of chapter 2 and in particular that farmer decision-making can be embedded into the HAPPenInGS theory. Furthermore, the research presented in this chapter tackles questions on social mobilisation for collective action that remained untouched in the case of neighbourhood support presented in the previous chapter: How do socially active initiator

[3] We wish to thank the European Commission for funding under the FP 6 NEST programme. We are much indebted to Karolina Królikowska (University of Wroclaw) for conducting and evaluating interviews with regional stakeholders. We also greatly appreciate the contribution of Grzegorz Holdys (Wroclaw University of Technology) who implemented the hydro-agricultural model.

persons influence collective action? What is the impact of financial incentives on collective action? Finally, how do structural asymmetries of the social dilemma effect social mobilisation?

The chapter proceeds as follows: Section 5.1 sketches the project context and motivates the presented research. A subsequent section reports on the set of issues that characterise the complex of problems encountered in the case study, extracts the central problem features to be covered in the model, and links these to social dilemma research. Section 5.3 demonstrates that decision-making of the members of the farmer community may be described in the HAPPenInGS theory and embeds the additional structural properties of the case in the theory framework of social dilemmas. This is followed by a detailed description of the integrated model itself, in particular its ABSS component. Section 5.5 documents simulation results, and the last section discusses and provides an outlook on future work.

5.1 Project context and introduction

The CAVES project contributed to the understanding of complex human-environmental systems by means of simulations based on integrated biophysical, social and policy models. To achieve this aim, key phenomena of complex human behaviour regarding land and water use in three case studies were studied. The main focus of the research conducted during the project was on the influence of social networks on environmental behaviour. CAVES included case studies in Great Britain, Poland, and South Africa to acquire data on real world evidence of social networks.

The Polish case study, with input provided by the University of Wroclaw and the Wroclaw University of Technology, is located in the middle course of the Odra River (see Figure 31) close to the Polish border to Germany. It focuses on those parts of the river catchment that are at risk of regular flooding in case of high water levels of the Odra. Experts propose that the negative effects of excess water stress could be mitigated (or possibly eliminated) by reinstalling a land reclamation system (LRS) that is neglected at present. Maintaining or re-establishing the LRS requires social mobilisation of the farmers concerned. Thus it is important that the acquaintance and/or friendship relationships that exist amongst farmers are utilised appropriately. Moreover, it is suspected that land reclamation, being a collective action, possesses the structure of a social dilemma.

The decision making of farmers about participating in the maintenance of the LRS is one of the main sources of complexity in the Odra case when coping with water stress. It touches aspects of social activation under conditions of a more or less fluctuating (hostile) environment. In addition, the environment sets complex hydrological inter-farmer dependencies. Thus, despite the multi-facetted farmer decision making concerning various topics (land-use, LRS, high-level economic considerations like buying/selling land, leaving or entering farming business, etc.) the work presented in this chapter focuses on a rather isolated examination of the socio-environmental dynamics of farmers' LRS decisions.

ABSS approaches are especially suitable for these kinds of domains because they allow for a bottom-up representation of individual actor's decision making based on local (subjective) perceptions of a common social and biophysical environment. The goal of the ABSS presented in this chapter is to test how assumptions about farmers' social and economic orientations drive or inhibit the installation of a working LRS under different social and policy conditions.

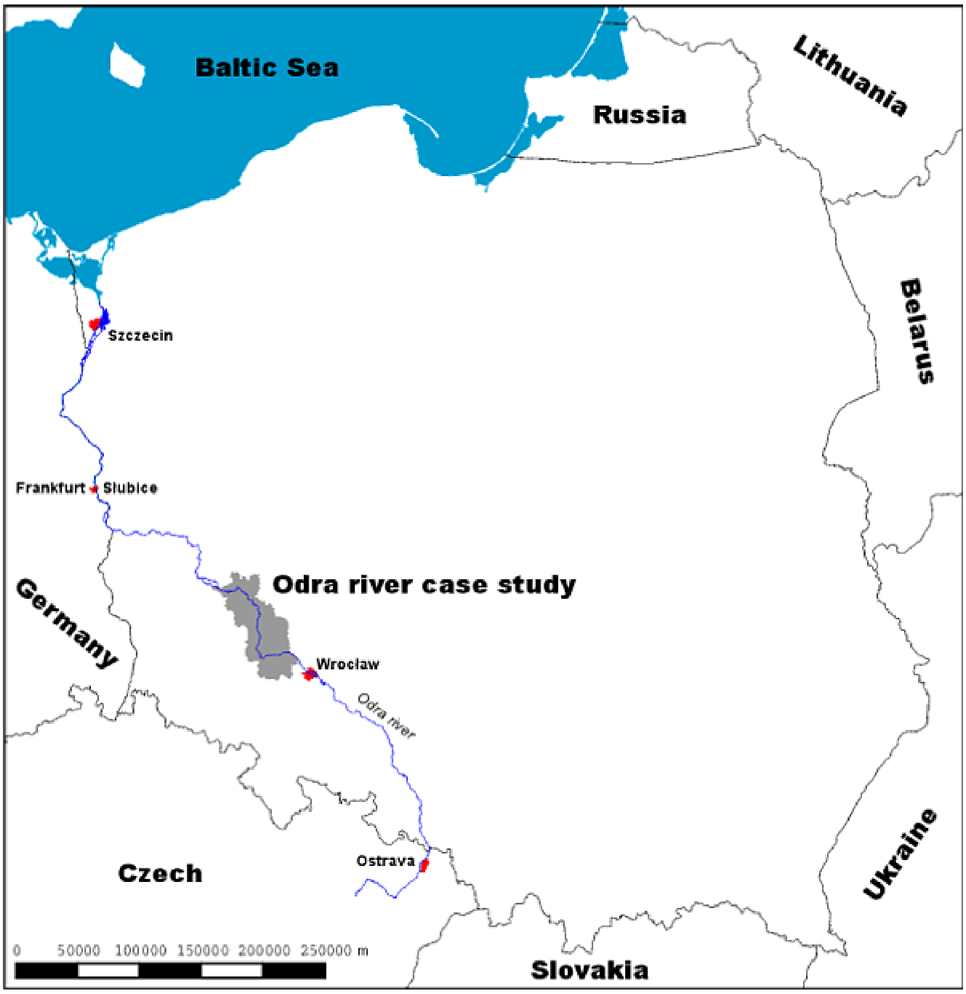


Figure 31. CAVES Odra river case study location[4].

The integrated simulation model of the Odra river region consists of two main components: The hydro-agricultural model provides insight into the costs and benefits of farming and land reclamation under certain climatic conditions. Complementing this, the ABSS called SoNARe (Social Networks of Agents' Reclamation of land) seeks to capture key aspects of the reasoning of the actors involved and their interactions with their biophysical and social environment. It is based on an explicit representation of social influence that is exerted and

[4] The map was prepared by Maciej Sieczka, University of Wroclaw.

perceived in social networks on the one hand and the individual agents' perception of economic success that is derived from feedback of the coupled hydro-agricultural model on the other hand.

5.2 *Empirical background and motivation*

5.2.1 Main actor types and decision-making

The investigation of the decision dynamics involved in land reclamation in the Odra region starts with the identification of the most important types of actors. In the work presented here we had, in addition to expert consultations, the opportunity to use transcripts of interviews that were conducted with farmers in the target region.

The central actor type is the typical small-scale farmer. When asking these farmers about their motivations concerning LRS maintenance, their statements may be roughly grouped into economic considerations pertaining to their farming success and social aspects that take into account the behaviours and opinions of other farmers in their community.

The economic dimension of LRS maintenance is mainly determined by the achieved stability in attained crop yields over years with climatic extremes on the one hand and by the required investment (financial or in terms of labour input) for performing the maintenance tasks on the other. In the interviews the involved uncertainties of an investment in LRS maintenance are e.g. reflected in the fact that the majority of farmers are aware of the relation between the state of the LRS and yields but they are not able to quantify the interdependency precisely.

The social dimension of LRS maintenance is constituted by the social support farmers perceive for their opinion as regards investment in LRS. Social support towards LRS maintenance may e.g. originate from other farmers maintaining their local LRS facilities properly and gaining protection against excess water. The opposite effect of high social support against LRS maintenance is presently observed in the target region: Nobody invests in LRS maintenance and therefore there is a strong social support to stay passive. From the interviews this aspect of difficulty in social mobilisation may clearly be seen because farmers seem to know about the interconnected nature of the LRS but tend to stay passive because they do not expect that others will join the collective action.

A second source of social influence pro LRS originates from actors actively trying to initiate a working LRS. Usually, these initiators are people from local authorities. In addition, farmers can also be convinced by other persons, who are socially skilled and rather well known (thus having high social network integration) as well as respected in the local community. For instance, farmers mention professional advisors forming advisory centres. The activity of such opinion leaders would usually be triggered by a set of conditions observed in a target region of such a campaign like favourable biophysical environment combined with low farming success. As an abstraction we regard all these types of leader personalities as LRS initiators in that they influence farmers in their decision to maintain the LRS and to participate in the collective action. Accordingly, LRS initiators form the second actor type that is relevant to the LRS decision dynamics.

5.2.2 The collective action of land reclamation

The LRS consists of canals and ditches (in the following, the term 'channel' is used for both canal and ditch) that drain the soil directly or through a system of drainage pipes, and thus the LRS protects a field against flooding by draining it quicker. To be effective the LRS requires regular maintenance. The LRS maintenance process mainly involves the periodic cleaning of canals and ditches, e.g. by removing vegetation and sediments from the channels' beds (see Figure 32 and Figure 33 for an overgrown ditch and a well maintained one, respectively). Due to the fragmented land ownership in the Odra region there is usually a group of riparian landowners along an LRS channel who are each individually responsible for local maintenance of a channel section.

Consequently, the LRS has the classical properties of a public good as outlined in section 2.1.1: Firstly, the LRS is provided by means of a collective effort of the group of farmers owning land along the respective drainage channels. Secondly, all farmers of the group benefit from a working LRS independent of their respective contribution. Hence, the individual farmer's decision-making on whether to increase the quality of the overall LRS by cleaning their section of the channel system is governed by a social dilemma.

To the extreme ends, LRS provision fits well the theoretical conception of a public good dilemma: Full social mobilisation ensures high degrees of flood protection to all farmers of the providing group. Likewise, collectively passive behaviour results in substantial crop losses for all landowners.

However, in the case of unequally distributed contributions the problem of LRS provision deviates significantly from the stylised theoretical notions of a production function and equally distributed benefits of the public good (as it is often the case for “real world” social dilemmas). This is mainly due to hydrological dependencies between neighbouring landowners along the LRS: Well-maintained downstream sections of a channel of the LRS increase the degree of flood protection for an upstream landowner independent of the LRS condition on the upstream land parcel. Furthermore, head-end farmers of a blocked sequence of LRS channel sections experience the highest water discharge, while tail-end farmers of a maintained sequence of channel sections face (slightly) increased water levels because of the upstream runoff that is drained through their land parcel. Therefore, both the effect of an individual contribution to the “production” of the LRS and the individually obtainable benefits of a working LRS differ depending on the farmer’s position along the channel.

In addition to the spatial heterogeneity of obtainable benefits, positive effects of the LRS are to a degree uncertain because a working LRS is most effective under unpredictable extreme weather conditions whereas under conditions of moderate precipitation the favourable effects of the LRS are negligible. Furthermore, farmers seem to perceive a strong social norm against LRS maintenance which keeps individuals from becoming active. Finally, during the past decades, farmers could claim compensation payments for crop losses caused by high water events, which significantly reduces the economic risk of a degraded LRS.

For the local authorities, to promote a reinstallation of the LRS in the Odra region it is essential to gain an understanding of the dynamic interplay of the factors that drive or inhibit social mobilisation of the farmers. An ABSS of the dynamics of LRS provision can help investigating different mobilisation scenarios. In order to reflect the situation characteristics outlined above such a social simulation has to focus on the interplay of economic and social incentives for LRS provision. Furthermore, the ABSS has to be coupled to a biophysical model that reasonably reflects the hydrological conditions in the target area and their relation to attainable crop yields. Especially under conditions of reduced compensation payments, the incentive structure underlying collective LRS maintenance will increasingly shift towards the outlined social dilemma.

Figure 32. A neglected overgrown ditch of the Land Reclamation System in the Odra region.

Figure 33. A well-maintained ditch of the Land Reclamation System in the Odra region.

5.3 Theoretical embedding

This section embeds farmer decision-making into the HAPPenInGS theory and briefly summarises the main structural properties of land reclamation in the Odra region from the perspective of social dilemma research.

As outlined in the section 5.2.2, the anticipated shift of the political boundary conditions will increase the influence of the social dilemma underlying the provision of a well-functioning LRS in the target region. Therefore, as described above, a maintained drainage channel of the LRS may in principle be conceptualised as a public good which is provided by the labour inputs of the riparian farmers. Consequently, farmer decision-making may be described by the HAPPenInGS theory. Figure 34 illustrates the respective specification of HAPPenInGS.

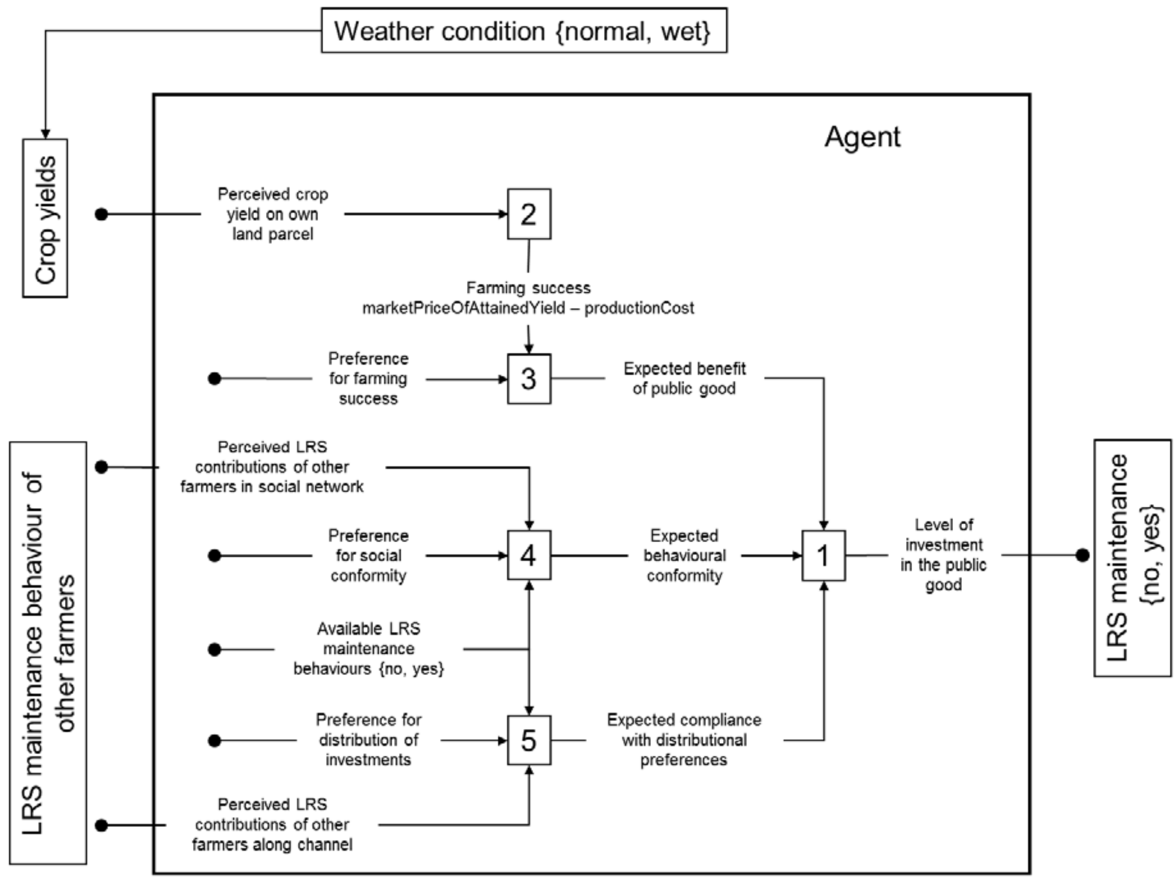


Figure 34. The instantiation of HAPPenInGS for the case of LRS provision. Arrows show the variables with their names and illustrate the sequence of their processing in the numbered blocks. See text for further explanations.

In order to specify the HAPPenInGS instantiation for the case LRS provision we describe the interfaces of individual decision-making to case-specific representations of the social and environmental contexts. The behavioural target variable is a farmer's local *LRS maintenance* consisting of cleaning his specific section of the LRS channel. We assume the decision to be binary in nature, i.e. maintenance is either performed or it is left undone. In turn, the respective LRS maintenance behaviours of the members of a farmer group located along an LRS channel determine the channel's overall effectiveness in draining excess water during extreme weather. According to HAPPenInGS, individuals assess the success of their group in providing the public good in relation to its salience under given external conditions. For the case of LRS provision, this feedback is given by a farmer's attained *crop yield* during a given year. Yields jointly mirror the local effectiveness of the LRS, its importance given the respective *weather conditions*, and the overall hydrological conditions on a farmer's field depending on its position along the channel.

In the social environment, individual behaviours are exposed to other individuals. Individuals perceive the *LRS contributions of other farmers in their social network*.

Finally, according to HAPPenInGS, individuals perceive the contributions of other members of their providing group in order to assess the distribution of investments. However, due to the lack of applicable case study data, in the ABSS presented below we disregard the influence of the corresponding distributional preferences on individual decision-making. Accordingly, the weight of *Expected compliance with distributional preferences* is set to 0 during decision-making.

Whereas information on farmers' social orientations is not available for Odra case, section 5.2.2 outlined a number of typical structural properties that influence decision-making on LRS maintenance.

On the one hand the case study description given above illustrates some typical properties constraining cooperative behaviour: First, the uncertainty of the benefits from the LRS depending on unpredictable climate conditions inhibits cooperation because decision-makers lack full knowledge about important parameters of the dilemma's structure (see section 2.1.2.2). Likewise, the complex spatial interdependencies between farmers add to this dimension of environmental uncertainty. Furthermore, the distribution of compensation payments changes the economic incentive structure of LRS maintenance and promotes defective behaviour in the public good dilemma. Finally, social coherence towards passive behaviour prevents initial mobilisation which is a typical phenomenon of normative social influence within the farmer community that dominates decision-making (see section 2.3.2).

On the other hand, two typical solution concepts for social dilemmas can be identified from the case study description: First, the activity of LRS initiators and their anticipated social acceptance is a classical solution approach to social dilemmas well in line with empirical results on social coordination and mobilisation (see section 2.1.2.3). Second, compensation policies could by adapted such that cooperation is rewarded rather than defection.

The ABSS presented in the following section will be used to investigate the impact of the proposed solution approaches on the social mobilisation of simulated communities where individual farmer decision-making is founded in the HAPPenInGS theory.

5.4 *Agent-based social simulation setup for the case of land reclamation*

This section reports on the integrated model that was developed for the described Odra case. We start with a systematic overview of the case study characteristics included in the model. The following subsections report on the two involved sub models, the agent-based core component and the linked model of the biophysical environment.

5.4.1 Integrated model overview

Figure 35 shows a diagram of the modelled system and its external drivers. The diagram covers only the key components of the system and serves to define system boundaries and to illustrate the main dynamics involved. In describing the diagram, we will also state the simplifying assumptions that were made in the modelling process.

On the left of the diagram there is a sketch of the biophysical subsystem showing a number of land parcels located along a common channel of the LRS. Land parcels are assumed to be identical in size and each parcel is managed by one farmer agent who is in addition embedded in the social environment given by the modelled farmers' community. The common social environment of the farmer agents is abstracted as a social network and agents exert and perceive social influence in the form of messages of social support or disapproval through the network ties. The LRS initiator agent is added to the social network with outgoing network ties to all individual farmer agents of the community, i.e. the initiator may exert social influence in addition to the inter-farmer exchange of messages.

Individual farmers interact with their biophysical environment by the execution of farming activities on their respective land parcel. Farming activities are composed of the yearly cycle of cropping activities and optional LRS maintenance efforts depending on a farmer's opinion on LRS maintenance. In the model, the yearly cropping activities of the farmers are abstracted as a fixed and yearly recurring economic investment (reflecting labour input as well as financial investments) in the cultivation of a farmer agent's field. While in the model farmer agents do not decide on if and how to cultivate their field they do decide on the maintenance of their local section of the LRS. Again, this optional input of labour is abstracted as a fixed additional economic investment in resource management that results in well working LRS channel on the farmer's field. The central feedback from the simulated environment to the farmer agents is constituted by yearly profits. Profits are a balance of the investments in the farmer's field including optional investments in LRS maintenance vs. revenues from selling the attained crop yield. Farming profits are driven by two external drivers: an economic driver composed of the market prices for the crops and the required investment in LRS maintenance and a climate related driver that determines the magnitude of water inflow by precipitation. Extreme water inflow in combination with a neglected LRS reduces crop yields and thus reduces profits.

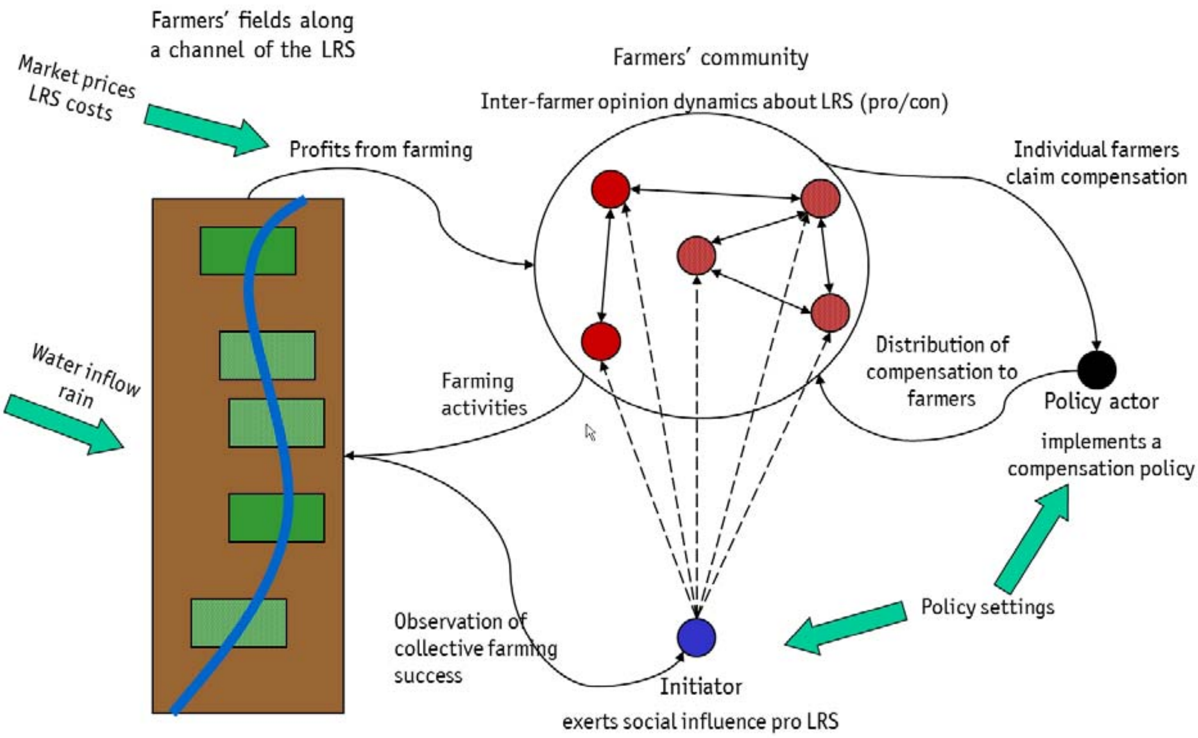


Figure 35. Land Reclamation (LR) in the Odra region. Biophysical environment, social environment, main actor types, and external drivers.

The LRS initiator agent observes the farming success of the community and starts to campaign pro LRS if the collective farming success remains low over a sequence of years. The activities of the initiator may be subject to certain favourable or inhibiting external policy conditions.

Finally, farmers can claim compensation payments from the local government, represented as a stylised policy agent, if their profits fall below a certain threshold. Depending on the compensation policy in effect the policy agent distributes compensation payments to the farmers which in turn influence the farmers' economic balance for a given year.

5.4.2 The Simple Hydro-Agricultural Model

The Simple Hydro-Agricultural Model (SHAM; Holdys, 2007) is a quasi-two-dimensional abstraction of the environmental situation typical for the Odra region. It reflects the hydrological dependencies between neighbouring landowners and simulates the effects of different weather conditions, LRS maintenance and LRS neglect on the water levels and the crop yields of individual land parcels along a channel. The outputs of the SHAM were - on the given level of abstraction - validated by the developer with stakeholders and experts.

5.4.2.1 Model setup

SHAM assumes a fixed number of land parcels located on a terrain of homogeneous slope, along a homogeneous LRS channel, that runs through the centre of every parcel. All parcels are assumed to be arable crop land and identical in size. Furthermore, the channel sections located on the parcels are identical in length and only differ in their respective position along the flow direction of the LRS channel. The model works with a monthly time step and in each time step, for every parcel, it calculates average soil water levels, conditions of channel segments and biomass growth. Here, the monthly time step is important to capture the seasonally varying sensitivity of the crop to water stress. At month 10 of each year the biomass is removed from the model and reported for each land parcel as the attained yield harvest of the respective year. The maximum possible yield on a field is ten tons per ha. We assume fields of identical size and only one crop type. Therefore, the maximum possible revenue from selling a year's harvest is identical for each land parcel and set to 10 monetary units. The yearly revenues provide the farmer agents with a feedback of the success of their farming activities and are used in the agent-level profit calculations (see section 5.4.3.1).

In SHAM, the condition of the LRS on a given channel segment is represented as a real number where 1.0 stands for a fully maintained section and 0.0 is the minimum value reflecting a blocked section. Weather conditions are set globally on a yearly time step to either moderate precipitation (normal year) or high precipitation (wet year). Weather conditions determine the total amount of water in the system only for one year and do not influence conditions in subsequent years. Excess water is either drained through the LRS channel or it remains on a land parcel depending on the LRS condition on neighbouring parcels. Water stress occurs on a land parcel if soil water levels exceed a certain threshold. For each channel segment, LRS maintenance may be switched on or off. When maintenance is off on a segment, the condition of the local LRS slowly degrades with a rate of 10% per month. When LRS maintenance is on, it fully recovers within a month, i.e. the LRS condition is set to 1.0.

5.4.2.2 Dynamics

This section documents the temporal and spatial dynamics of SHAM. We assume continuing cropping cycles on each land parcel and only investigate the influence on different configurations of section-wise LRS conditions on crop yields. For the results presented here, SHAM was configured for a total of ten land parcels located along one channel of the LRS - higher numbers of land parcels per channel are rarely observed in the target region. Parcels are numbered starting from parcel 1 most upstream to parcel 10 at the end of the channel.

Figure 36 summarises the process of LRS degradation and corresponding effects on yields under normal and wet weather conditions. In the first simulation year we assume that the LRS is fully functioning, i.e. all ten sections are well maintained. Starting from year 2, LRS is neglected on all ten land parcels and degrades. The red dotted line in Figure 36 shows how the condition of the LRS degrades with a rate of 10% per month. The boxplots in Figure 36 show the yields attained on the ten parcels per year. For normal weather conditions SHAM shows a negligible impact of the LRS condition on the crop yield (green boxes located left to the year ticks) for parcels located downstream from parcel 1. From year 3, when LRS condition has degraded to 20%, the crop yield on parcels 1 decrease even under moderate weather conditions (see the marked outlier in the box plots). In wet years, a maintained LRS generally increases the crop yield (blue boxes located right to the year tick) with a higher effect upstream. Also, when the channel is well maintained on tail-end parcels a loss in yield is experienced because excess water from the upstream parcels is drained through their channel sections to a degree exceeding the capacity of the LRS channel. As the LRS degrades, head-end parcels have substantial losses due to excess water stress. In turn, tail-end parcels obtain a degree of implicit flood protection form the fact that portions of the excess water are absorbed by fields located further upstream.

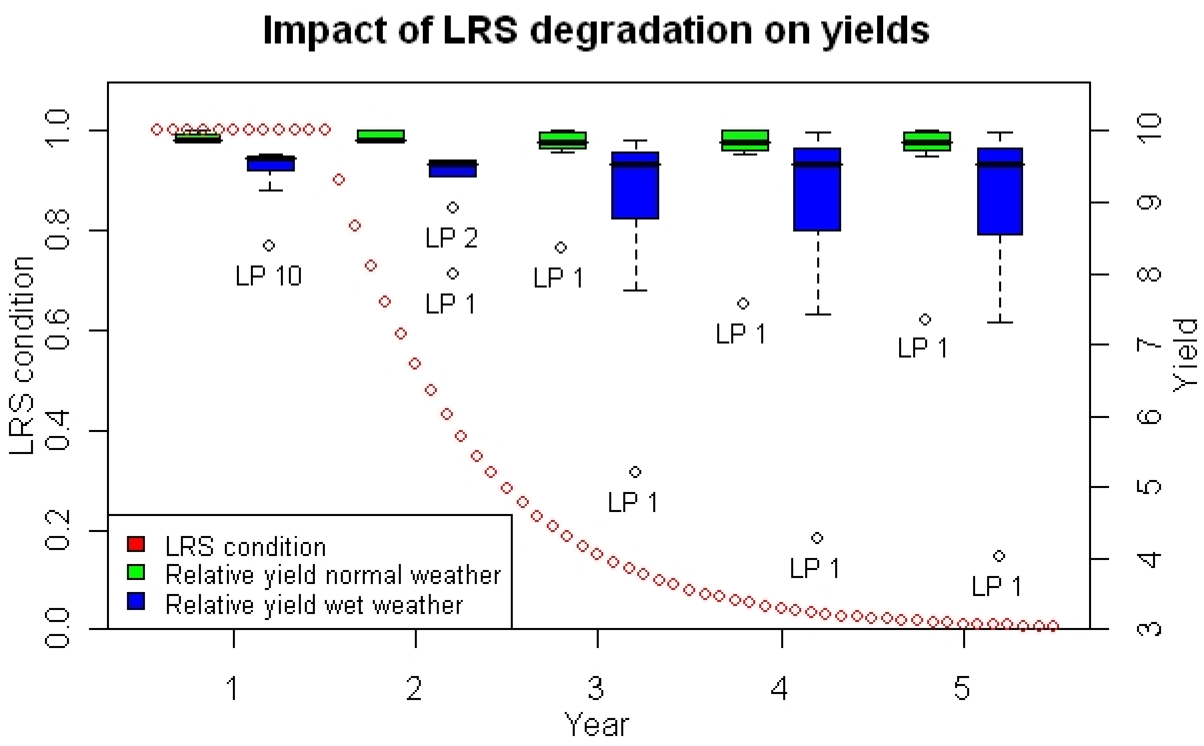
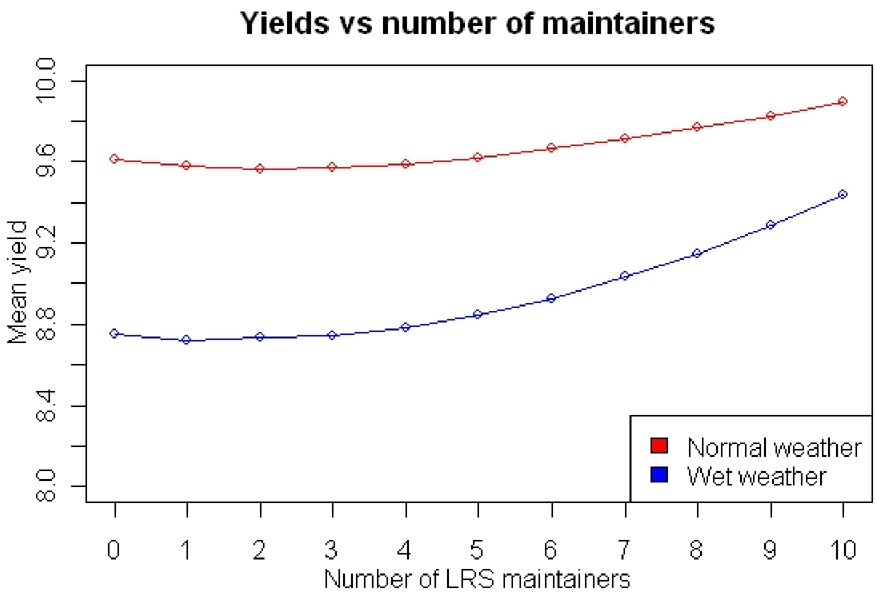


Figure 36. Simulation results for a channel of ten land parcels. The LRS is maintained on all parcels in year 1 and degrades from year 2. LRS condition is displayed in red, starting from 0 (neglected) to 1 (fully functional). Box plots show the yields on the ten land parcels over time for normal years (green) and wet years (blue). Outliers are labelled with the respective parcel number with land parcel LP 1 located most upstream.

Figure 37 illustrates the interrelation between the number of maintained channel sections, and average crop yields respectively the standard deviation of yields. The diagrams show on the ordinate averages over all possible spatial distributions of a fixed number maintained channel sections along the channel. The most visible effect of a collectively managed LRS seems to be the reduced inequality in attained yields (see bottom diagram of Figure 37). In summary, yields moderately increase with the number of maintained channel sections while the inequalities of yields between land parcels decreases.



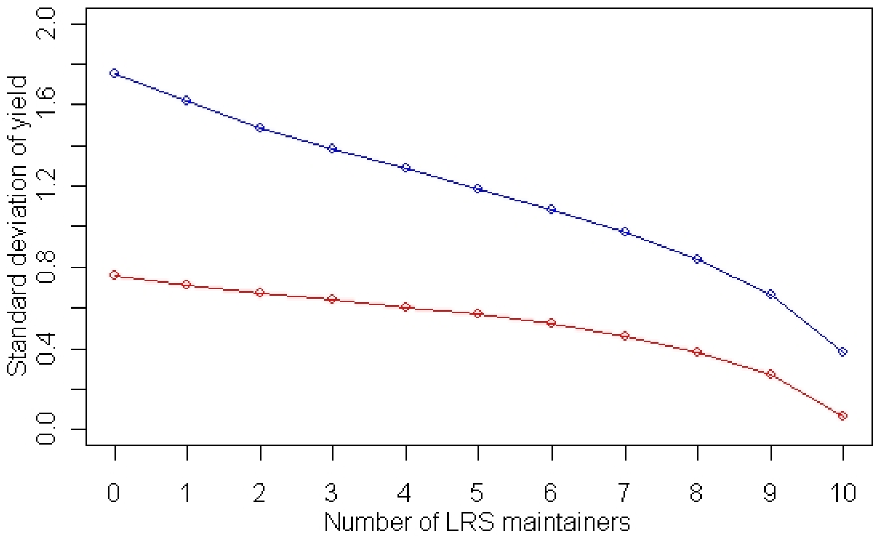


Figure 37. Simulation results for different numbers of LRS maintainers. The diagrams show mean values of the yields for all spatial setups of a given number of maintained channel sections under normal and wet weather conditions respectively. The upper diagram depicts the average yields; the lower diagram shows the standard deviation of the yields.

The relationship between weather conditions, local LRS condition on a channel section, and the obtained crop yield on a field along the channel induces an incentive structure that influences decision-making on an investment in LRS maintenance. In order to analyse the structural properties of the decision situation, we assume that each field along the channel is owned and managed by one and only one individual decision-maker. In SHAM, the behavioural dimension is given by two distinct options at an individual's disposal, which are either to invest in LRS maintenance of not. Behavioural incentives are defined by the respective yields reflecting the individual's behaviour as well as the behaviours of all others in the same time step.

As expected, the social dilemma character of the situation is most obvious at the extreme ends of collective behaviours: As illustrated in Figure 37, especially under wet weather conditions the mean yield is significantly increased when comparing the case where the number of LRS maintainers is 0 to collective LRS maintenance. However, for a completely unmaintained LRS the standard deviation of yields is 1.8 units, which is 20% of the mean. This implies that land parcels exist where yields substantially deviate from the mean, suggesting that by no means all individuals benefit from collective LRS maintenance.

This asymmetric situation is further illustrated in Figure 36 when comparing yields for an LRS channel that is maintained in all ten sections (year 1) and an LRS that is unmaintained in all ten sections (year 5, fully degraded): For year 5 and wet weather the whiskers of the blue boxplots not only extend further towards low yields, they also extent further towards high yields when compared to year 1. In other words, on some land parcels yields increase as the LRS degrades. This effect is particularly significant for LP 10 when comparing year 1 and year 2. In year 1, due to its position at the end of the channel LP 10 is an outlier and has a yield of around 8 units. In year 2, when the LRS is degraded to about 50%, the yield on LP 10 is within the blue box, i.e. above 9 units. Concluding, at least for LP 10 yields can increase as the collective effort to maintain the LRS decreases.

For the simulation results presented below, we configure SHAM for a total of ten LRS channels each subdivided into ten independently managed sections. While within each of the channels the described asymmetric dependencies between the riparian land parcels exist, the individual channels are assumed as hydrologically independent, i.e. they are not interconnected.

5.4.3 The SoNARe model

This section reports on the ABSS core of the integrated model called SoNARe (Social Networks of Agents' Reclamation of land) that aims to capture farmer decision-making and some of the main social characteristics of the Odra case in an ABSS. SoNARe is coupled to SHAM which provides the agents with perceptions of profits from crop yields under fluctuating climate conditions in the simulated area and simulates the effects of their individual behaviours.

The following subsections report on the implementation details of SoNARe. We first give a specification of a farmer's perception of his past economic success that allows it to appraise its past behaviour from a purely economic point of view. Then we specify the farmers' social environment and define how a farmer perceives his network to form a social appraisal of his behaviour as regards LRS maintenance. Following the formalisation, an agent's opinion on his past behaviour is formed as a weighted sum of the economic and social appraisal values. Therefore, in the final subsection we introduce this socio-economic orientation as a parameter of heterogeneity of the individual farmers.

5.4.3.1 Economic success

As stated above we assume that each individual farmer agent manages one field and that fields are identical in size. Thus, fields only differ in terms of their respective location along a channel, and in the condition of the local LRS section. The feedback about crop yields and corresponding revenues is provided by SHAM. Market prices are assumed fixed throughout a simulation run. Revenues from selling a year's harvest on the market are normalised such that they range from 0 units for a full loss of harvest to 10 units reflecting market price of the maximum attainable yield. Individual farmers' costs are composed of investments in crop production and optional cost for LRS maintenance (depending on a farmer's LRS maintenance action). Thus, at the end of a simulated cropping season a farmer's economic balance is calculated as follows:

Profit = marketPriceOfAttainedCropYield – productionCost – costLRS

Farmer agents use their individual profit to appraise their respective behaviour of the past simulation year. For this purpose they assess their profit as -1 (“too low”) or +1 (“ok”) with respect to an aspiration level (Simon, 1955) that reflects the expected minimum profit (a fixed threshold value is used for all farmers). This profit appraisal is memorised with a retention time in years which is fixed per farmer agent but heterogeneous among agents. The memory structure of an agent is composed of a set of tokens that are triples of profit appraisal, LRS strategy, and retention time. For instance if agent A has a retention of 5 years then a memorised profit appraisal will persist for 5 years and after that be removed from the memory. When evaluating a past behaviour (pro/con LRS) farmers consult the relevant tokens stored in their memory, sum up the associated profit appraisal values and normalise to the codomain [0,1] such that values below 0.5 represent “negative economic success“ while values equal to or above 0.5 reflect “positive economic success“. During decision-making, this calculated economic appraisal (*economicAppraisal*) of an agent’s past behaviour is used to quantify its attitude towards its past behaviour (see section 5.4.3.3).

The following table summarises the relevant parameters and the values used.

Variable name	**Value used**	**Description**
marketPriceOfAttainedCropYield		Provided by SHAM; between 0.0 and 10.0 units
productionCost	8.0	Investment in farming activities (excluding LRS) per year. The value was estimated in relation to the maximum attainable yield (market price is 10 units). Maximum possible profit is 20% (=2 units) of the market price of the maximum yield on a field.
costLRS	0.5	Amount (or work equivalent) per year that has to be invested in the LRS if it is maintained
profitThresholdFarmers	0.5	If a farmer's profit in a year drops below *profitThresholdFarmers* then the profit (of that year) is considered "too low" otherwise "ok"
minRetentionTimeFarmers	3	Individual retention times are distributed heterogeneously among agents. Retention times are assigned to farmers from a uniform random distribution from [*minRetentionTimeFarmers*, *maxRetentionTimeFarmers*] The random seed of the distribution is set to *memRngSeed*.
maxRetentionTimeFarmers	7	
memRngSeed		

Table 9. Economic success: SoNARe parameters, values, and descriptions.

5.4.3.2 Social networks

The agents' social environment is modelled as a network. We investigate the exertion and perception of social influence as ways of "acting in" and "perceiving" a given social environment. In order to clearly isolate the effects of possible topological network dynamics (adding or removing edges) we use a one-layer and static social network. This network only serves as the infrastructure for perceiving and exerting social influence.

Farmer agent and the LRS initiator differ distinctly in the ways they are embedded in their social and physical environments. In the model, both agent types are embedded in a common acquaintances network. The evidence that an LRS initiator has a high degree of social network integration is covered by the fact that the agent is linked to all farmer agents (in a star-like manner) whereas farmer agents possess direct social links (bidirectional) only to a fraction of other farmer agents (but the social links could span a number of hydrologically independent channels of the LRS). As the Odra case study suggests, most LRS initiator actors are not farmers themselves since they are e.g. village mayors or external advisors. Therefore, in the model these agents do not directly interact with the simulated physical environment. In contrast farmer agents continuously interact with the simulated environment by performing (or neglecting) local LRS maintenance and by obtaining feedback about attained profits from crop yields.

A farmer agent's perception of social support is a function of the agreement or disagreement concerning LRS maintenance with its social network acquaintances. An agent receives a signal of support from each acquaintance that shares its opinion regarding LRS maintenance in that year, whereas it receives a pressure signal from each agent that has the opposite opinion. The exertion of social influence is strictly symmetrical in the sense that a signal of support and a pressure signal sent by the same farmer agent are identical in magnitude. Furthermore, the magnitude of the social signals sent by farmer agents is set to 1.0 for all agents.

The LRS initiator agent being embedded in the social acquaintance network participates in the general opinion dynamics as regards LRS maintenance only in that it exerts social support to farmer agents maintaining their LRS and sending pressure signals to those neglecting the LRS. While farmer agents continuously exchange social messages an initiator agent only becomes active when certain conditions are met, see section 5.4.3.3. Signals of social support or pressure sent by LRS initiators are higher in magnitude than those sent by farmers. The strength of social influence exerted by an initiator is set in relation to that of farmers to a fixed value of 3.0, i.e. with the setting used the initiator is three times as influential as a farmer.

Like for economic success, the final indicator of an agent’s perceived social support is calculated as a normalised sum of all social influences such that values below 0.5 represent “negative social support“ while values equal to or above 0.5 reflect “positive social support“. The social support an agent perceives for his behaviour as regards LRS maintenance may be seen as an agent’s social appraisal (*socialAppraisal*) of his past behaviour. During decision-making this value is used as a proxy for the agent’s perceived subjective norm (see section 5.4.3.3).

The table below describes the parameters used and documents the respective settings.

<table>
<tr><th>Variable name</th><th>Value used</th><th>Description</th></tr>
<tr><td>networkType</td><td>WS</td><td rowspan="3">Watts-Strogatz network, small world network (ring substrate) generated by the RePast network factory with the following parameters:
rewiringProbability=0.1
connectRadius = avgAcquaintancesDegree / 2
RandomSeed is the seed of the RePast random number generator that is used during random rewiring</td></tr>
<tr><td>avgAcquaintancesDegree</td><td>10</td></tr>
<tr><td>RandomSeed</td><td></td></tr>
<tr><td>relativeInfluenceLevelInitiator</td><td>3</td><td>Strength of a social influence exerted by an initiator in relation to that of farmers, i.e. with the used setting the initiator is three times as influential as a farmer.</td></tr>
</table>

Table 10. Social networks: SoNARe parameters, values, and descriptions.

5.4.3.3 Decision making

The process for farmer agent decision-making is illustrated in Figure 38. Based on their perceptions (step 1), agents form a social and a non-social evaluation of their past behaviour (step 2). The definitions given in the previous two sections provide the quantifications of a farmer's social and economic appraisal of his past behaviour. The resulting opinion of an agent on his past behaviour is formed as a weighted sum of the two appraisal values (step 3). We implement this balancing by adding a parameter that reflects the (socio-economic) decision bias that a farmer agent has. The *decisionBias* of a farmer agent is represented as a value in the range of [0,1] where values above 0.5 stress the economic influence on decision making, values below 0.5 stress the social dimension. Since the two appraisal dimensions are normalised, the combined appraisal of a farmer agent is calculated as a weighted sum in which *economicAppraisal* is weighted with *decisionBias* and *socialAppraisal* is weighted with (1-*decisionBias*). This combined appraisal is calculated as follows:

combinedAppraisal = *economicAppraisal* * *decisionBiasFarmer* + *socialAppraisal* * (1 – *decisionBiasFarmers*)

The formation of a behavioural intention is abstracted in the form of a Win-Stay, Lose-Shift heuristics (Nowak & Sigmund, 1993), i.e. an individual intends to keep to his previous behaviour (contributing to the collective action or not) if the combined appraisal is sufficiently high with respect to an aspiration threshold, otherwise it intends to shift to the opposite behaviour. For the Win-Stay, Lose-Shift heuristics (step 4) we use an aspiration threshold of 0.5, i.e. a farmer agent keeps to its previous behaviour (maintaining or not maintaining the LRS) if *combinedAppraisal* is above 0.5, otherwise the farmer agent shifts to the opposite behaviour. Farmer agents are assumed to follow their formed intention and change their behaviour if the conditions are met. Therefore, the selected behaviour is executed by forwarding it to SHAM where the taken LRS decision persists for the following simulation year for a farmer's respective land parcel.

The LRS initiator is assumed to possess information about the farming success of its social network neighbours and decides to exert its social influence in favour of LRS maintenance whenever it perceives a minimum number of farmers who have big losses. The LRS initiator does not exert any influence otherwise.

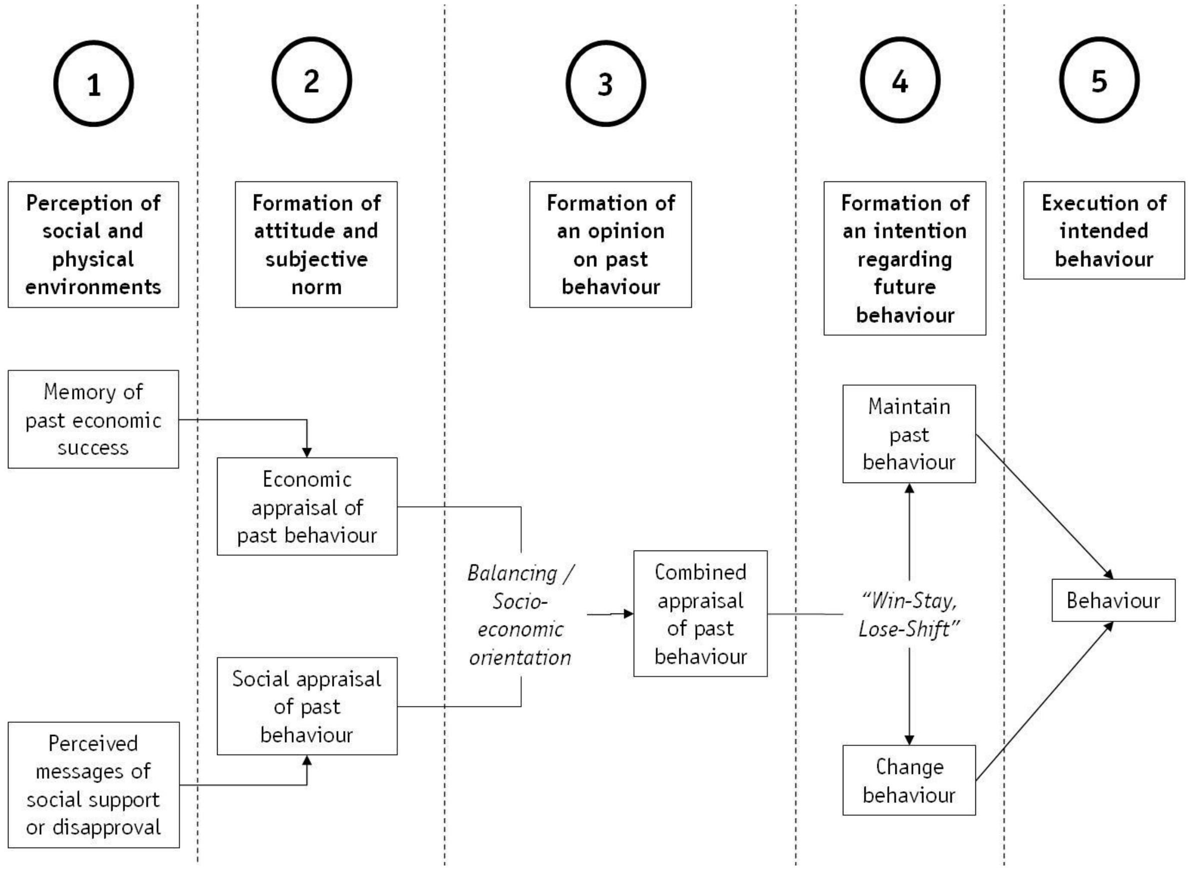


Figure 38. Formalisation of farmer decision-making. In step 1 an individual's perceptions of his social and biophysical environment are updated. Based on the perception in step 2 attitude and social norm are formed. In step 3 attitude and social norm are weighted according to an individual's socio-economic orientation which results in a combined appraisal of past behaviour. In step 4 this subjective opinion of an individual on his past behaviour is evaluated in relation to an aspiration threshold resulting in an intention regarding subsequent behaviour. In step 5 the intended behaviour is executed in the biophysical environment.

<table>
<tr><th>Variable name</th><th>Value used</th><th>Description</th></tr>
<tr><td>decisionBiasFarmers</td><td>0.5</td><td>Socio-economic orientation of the farmer agents, values above 0.5 stress the economic influence on decision making, values below 0.5 stress the social dimension.</td></tr>
<tr><td>bigLossesThreshold</td><td>0</td><td rowspan="2">At the end of a simulation year the LRS initiator observes the profit of each farmer and counts those farmers whose profit has dropped below bigLossesThreshold. The initiator keeps a track of these counts over the past 6 years, if the average of this track rises above initiatorActivationThreshold then the initiator becomes active and exerts social influence. In all other cases he remains passive.</td></tr>
<tr><td>initiatorActivationThreshold</td><td>10</td></tr>
</table>

Table 11. Decision parameters and values.

5.5 Results

This section reports on simulation results with SoNARe that were published in Krebs & Ernst (2008).

5.5.1 Setup and performance indicators

Simulations start out from the status quo observed in the Odra region: The LRS is not functioning and none of the farmers is willing to start maintaining it. There are no economic incentives for maintaining the LRS because farmers who experience crop losses during wet years are fully compensated by the regional government, i.e. the policy actor in the simulations always fully equalises farmers' crop losses by compensation payments. The first 10 years of the presented simulation runs are "warm-up years" that simulate this status quo and initialise profits, profit memories and social support perceptions of the farmers. Starting from simulation year 11 the described LRS initiator gets active. In addition, also starting from simulation year 11, a compensation policy becomes effective. We compare three different policies:

- Policy 0 - no compensation payments: Whereas farmers are always fully compensated during the initial 10 years compensation policy 0 assumes a full cut down of compensation payments.
- Policy 1 – reduced, unselective compensation payments: Policy 1 is not as strict as policy 0; it assumes an upper limit of compensation that may be claimed by an individual farmer per year. In the simulations the upper limit is selected such that under policy 1 around 20% of the farmers still undergo economic stress in a wet year if the LRS is completely neglected.
- Policy 3 - reduced, selective compensation payments: Policy 2 uses the same limited compensation payments but payments are only made to farmers who maintain their section of the LRS.

Simulations were conducted for 120 simulated years and a total of 100 farmers located along ten independent channels of the LRS and embedded in a common social network. Furthermore, a random weather sequence with repeating events of excess water stress was used. The weather sequence was generated by a uniform random number generator where for each year the probability to be a wet year was set to 30% otherwise a normal year was selected. The chosen weather sequence has 37 wet years and 83 normal years.

The comparative simulations discussed below are all based on identical initialisation settings as reported in section 5.4.3 including the sequence of wet and normal years, i.e. they only differ in the compensation policy implemented by the policy actor. The effects of the three compensation policies are compared with respect to three indicators:

- Indicator F, the farmers' perspective, reflects the severity of economic stress farmers are exposed to in terms of the percentage of farmers having positive profit. Low values of this indicator stand for high economic stress, i.e. high values are desired.
- Indicator P addresses the perspective of policy makers by calculating the relative cut-down of compensation payments in % compared to the status quo. Note that during the warm-up years of the simulations compensation inputs are equal for all policies and thus the relative cut-down percentages are comparable between runs. Again, high values are desirable from the policy maker's point of view.
- Indicator S looks upon a social / structural perspective and is represented by the percentage of farmers maintaining their local LRS; high values stand for high degrees of social mobilisation and for an effectively working LRS. In the following diagrams the development of the indicators over time is displayed as a rolling mean over 6 years.

5.5.2 Comparative scenario assessment

Figure 39 shows the development of indicator F over the simulation period for the three compensation policies. Most significant are the magnitudes of the phases of economic stress after year 10 when compensation is cut down. While F drops for policy 0 to below 80% until year 60, this effect is dampened for the other policies. Notably for policy 1 around 96% of the farmers have positive profit over the whole simulation period whereas for policies 0 and 2 after the phases of economic stress 100% of the farmers have positive profit.

Figure 40 shows the temporal dynamics of indicator P. For policy 2 the very limited compensation inputs when comparing to policy 0 (no compensation input at all) may be seen. In addition, the continuously high compensation payments under policy 1 that correspond to patterns of consecutive wet years a clearly visible.

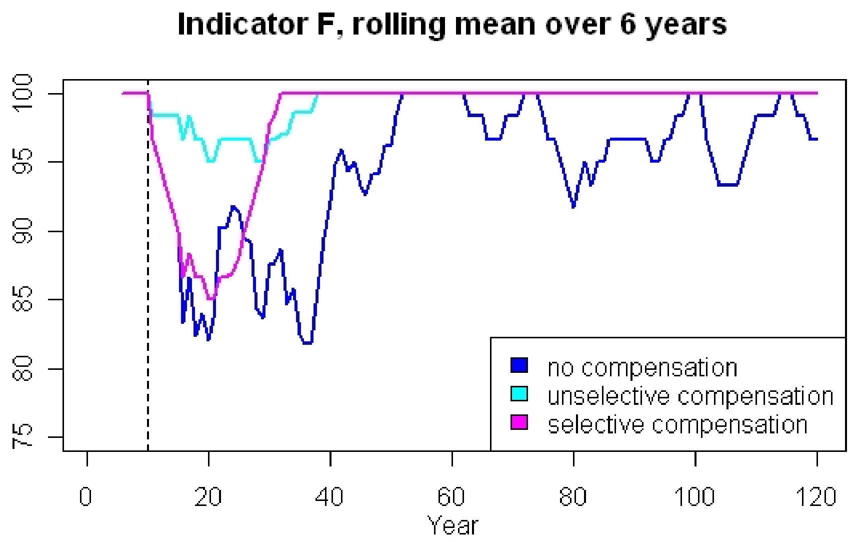


Figure 39. Percentage of farmers with positive profit, rolling mean over 6 years. Adapted from Krebs & Ernst (2008).

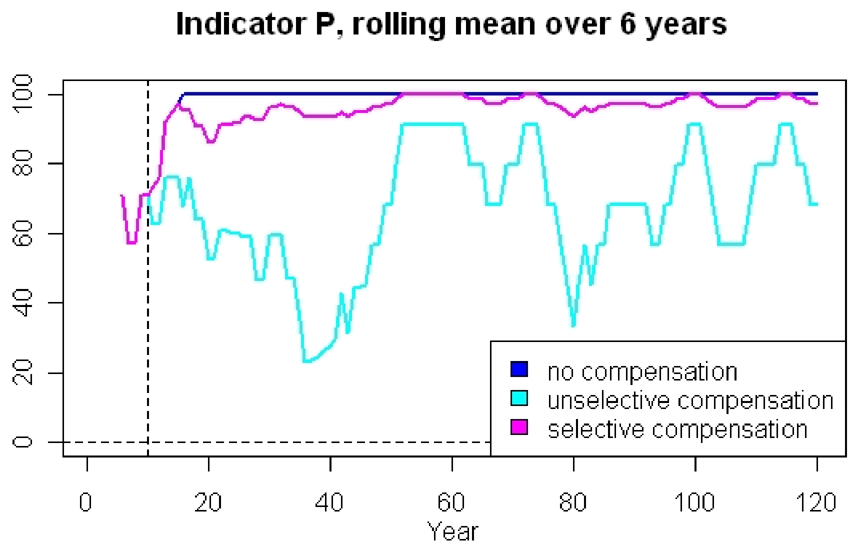


Figure 40. Reduction of compensation payments in % relative to status quo, rolling mean over 6 years. Adapted from Krebs & Ernst (2008).

Finally, the development of indicator S in terms of the percentage of farmers mobilised is illustrated in Figure 41. For policies 0 and 2 100% of the farmers are mobilised. Due to the selective compensation inputs, in policy 2 the mobilisation process is accelerated considerably when comparing to policy 0. In policy 1 the mobilisation rate stabilises at around 60%. For the remaining minority of 40%, profits are too high to make them change their behaviour despite relatively low social approval. The high profits of this subgroup are mainly generated by the permanent flow of unselective compensation in combination with positional advantages along a channel (farmers located downstream with a partially working LRS further upstream). Furthermore, the small fraction of farmers (around 4%) that continuously undergoes economic stress (see Figure 39) is located in a region of the social network in which social approval of their economically unprofitable behaviour is high enough to prevent an opinion shift.

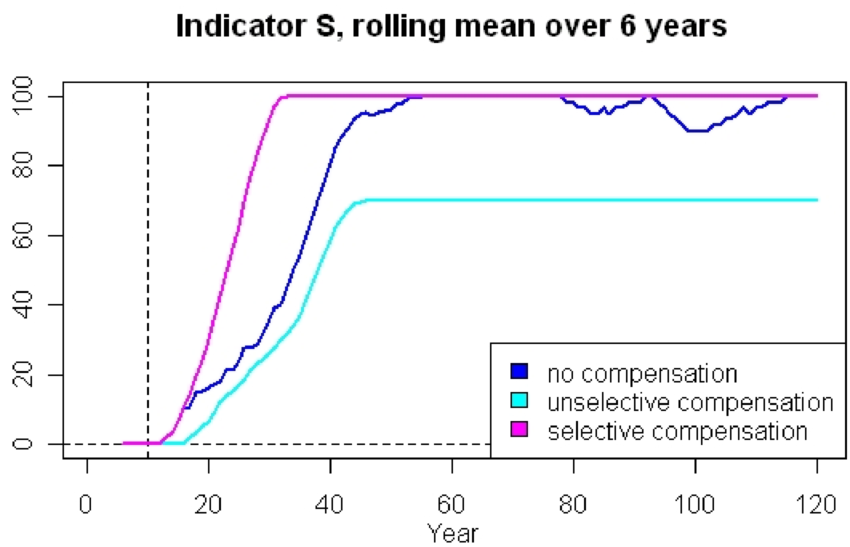


Figure 41. Percentage of farmers maintaining their local LRS, rolling mean over 6 years. Adapted from Krebs & Ernst (2008).

In order to directly compare and rank compensation policies we propose a multi-criteria assessment based on all three indicators and the complete simulation period. For this purpose aggregated indicators describing the temporal development of the three indicator dimensions are defined. Indicator F* assesses the economic viability of a policy from the farmers' perspective. The indicator is calculated in terms of the number of years in which at least 90% of the farmers have positive profit. Indicator P* is calculated as the mean cut-down of compensation over the simulation period. Finally, indicator S* is calculated as the average percentage of LRS maintainers for the simulation period. While indicator S* assesses the magnitude and speed of collective mobilisation of the system under a given compensation policy, indicators F* and P* directly assess the economic viability of the system. If F* is low then there are long periods where too many farmers cannot make their living from their farming activities and the compensation paid to them, which implies that many farmers would tend to quit farming altogether. Low values of P* stand for continuing high compensation inputs into the system which implies an ineffective policy.

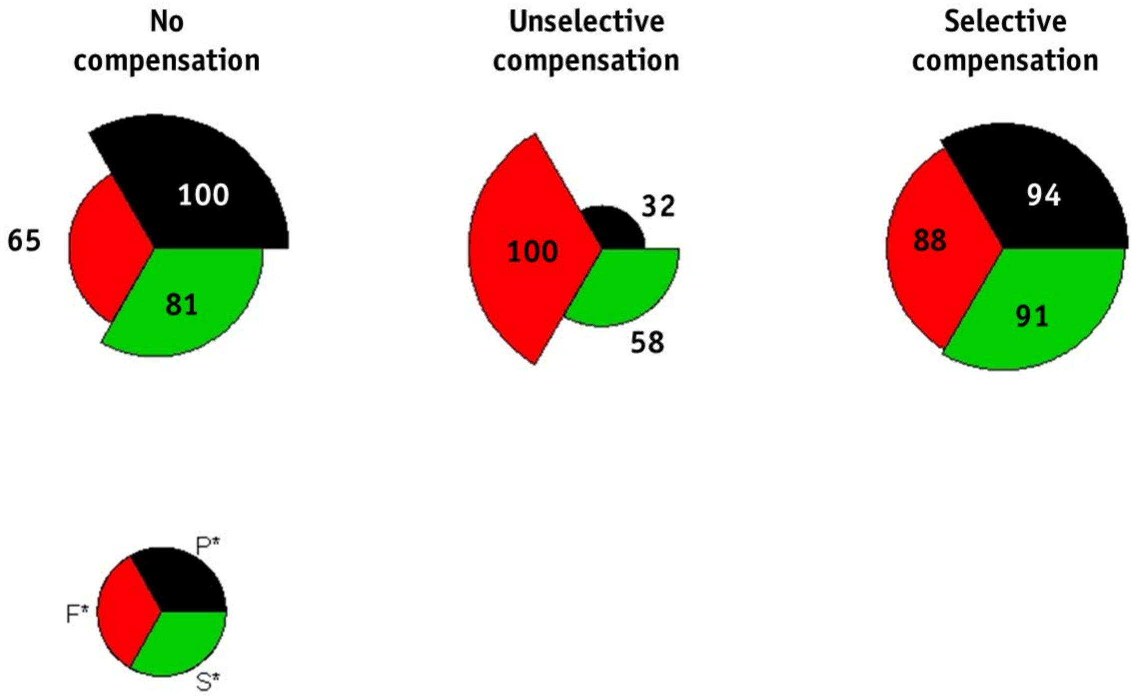


Figure 42. Indicator comparison over the whole simulation period showing the number of years where at least 90% of the farmers are profitable F* (red, 70 years to 100 years), mean relative compensation reduction P* (black, 50% to 100%), mean structural change S* (green, 0% to 100%). Adapted from Krebs & Ernst (2008).

Figure 42 shows the indicator assessment of the three defined policies as segment diagrams where the radius of each segment corresponds to the respective indicator value. The

segment diagrams show that high and fast structural change involves more or less pronounced phases of economic stress for the farmers. Most effective structural change is achieved by selective compensation payments to LRS maintainers in policy 2. In addition, application of policy 2 involves very low compensation inputs (close to 100% of reduction) while yielding higher structural change and higher farmer wealth compared to policy 0.
Moreover, it may be seen that the high wealth of farmers F* observed for policy 1 entails a clear drawback: little reduction of compensation payments P* and almost no structural change S*. The segment diagrams clearly show this imbalance of the three indicator dimensions for policies 0 and 1 whereas policy 2 entails a balanced attention to all indicator dimensions and is thus most viable.

5.6 *Discussion and conclusions*

The presented integrated model comprises an ABSS that is coupled to an abstract biophysical model reflecting the main hydro-agricultural properties typically found in the Odra river case study area. The ABSS SoNARe simulates the collective decision making of landowners in the target area under fluctuating boundary conditions set by the biophysical model. Landowner decision dynamics are represented by actor types, stylised behavioural rules, and well-founded psychological assumptions about social influence, memory capacity and social networks.

Even though the model is quite abstract it clearly demonstrates the interplay of individual economic drivers and social influence on one hand and external drivers set by climate and policy on the other hand. Simulation results motivate that despite the situation's underlying incentive structure prone to free riding, a social "activity seed" together with some economic pressure on the participants can be sufficient to trigger a social lock-in in favour of LRS maintenance.

The presented results show that the proposed multi-indicator assessment of a coupled model is fruitful. Results demonstrate, that the effect of socially active initiators of a collective effort can be further amplified by selective compensations payments to those already participating but undergoing economic stress. However, the beneficial effect of the initiator is undermined if compensation is paid unselectively to all farmers. The proposed indicator approach in combination with the visualisations as segment diagrams may be used to efficiently compare big numbers of simulation runs that differ in scenario settings or in random factors. Future work will focus on a more complete assessment of system behaviour by adding additional indicator dimensions that cover e.g. the social support between farmers or the magnitude of inequalities in farming productivity.

Finally, when taking the perspective of research strategy, the SoNARe model has to be understood as an important building block in a sequence of research steps that contributed to the HAPPenInGS theory, and which ultimately lead to HAPPenInGS-A and HAPPenInGS-N. Still, the "kinship" between SoNARe and HAPPenInGS-N is sufficiently close to enable an in-depth synthesis of the results from the two ABSS which is done in section 6.

6 Synthesis

In many real world contexts individuals find themselves in situations where they have to decide between options of behaviour that serve a collective purpose or behaviours which satisfy one's private interests, ignoring the collective. The introduction of this thesis sketched two particular real-world social dilemma situations, namely the case of neighbourhood help and the case of land reclamation, but examples abound. In some cases the underlying social dilemma is solved and we observe collective action. In others social mobilisation is unsuccessful. The goal of this thesis was to contribute to the understanding of this phenomenon for the case of public good dilemmas. The main method of the thesis is agent-based simulation of social systems (ABSS).

The purpose of this synthesis section is to summarise the research results of the thesis, to formulate the main conclusions to be drawn from the results, and to propose follow-up research. To do so, section 6.1 recaps the main theoretical contributions of the thesis and highlights the method developed. Following this, section 6.2 is devoted to the results of the simulation exercises and their respective implications. In the section, we start by overviewing the results of the dynamical analysis of the theory developed in an abstract ABSS setup. Subsequently, we summarise results from the application of the theory in two case studies. The purpose of section 6.3 is to derive overall conclusions by pulling together the different insights of the thesis and to propose future work.

6.1 Theoretical results and method development

6.1.1 Theoretical embedding of public good dilemmas

The thesis started by embedding the case of public good dilemmas into the broader domain of social dilemmas. In doing so, the classical game-theoretic conception of social dilemmas and its relation to existing real-world evidence was reviewed and discussed (cf. section 2.1). Starting out from the historical roots given by variants of the classical prisoner's dilemma game and their conception in mathematical game theory we concluded with the influential game-theoretic definition of a social dilemma by Dawes. The definition clearly frames the case of public good dilemmas, which is the core of this dissertation, as one instantiation of a social dilemma. Furthermore, Dawes' definition links the research branch to psychological questions.

Public good dilemmas are social dilemmas which focus on the collective production of a joint good. Such public goods are defined by two features: collective provision and non-excludability from the benefits of the public good. Hence, the social dilemma arises when individual members of a providing group decide whether to contribute to the public good provision (to cooperate) or whether not to contribute and only enjoy the benefits of the public good (to defect). The core problem feature is non-excludability which implies that mutual defection of all members of the providing group is a dominant strategy. While this deficient equilibrium of collective defection is an implication of classical game-theoretic analysis, it is challenged by a body of empirical studies that document the prevalence of cooperative behaviour in the form of collective action. This observation marks the mystery that lies at the heart of social dilemma research in general and public good dilemmas in particular: Why do people sometimes behave in ways that fundamentally contradict their objectively existing selfish interests?

Research on eliciting and understanding mechanisms that are effective in triggering cooperation in social dilemmas abounds. We reviewed the core results from the wide-ranging body of experimental and case-study-based empirical studies from social psychology, economics and sociology. The implications from this branch of research led to the two main theoretical contributions of this thesis which cover the situational embedding of individual decision-making in a public good dilemma and the heterogeneity of actors. The two following subsections recap these insights.

6.1.2 Systems perspective: Public good dilemmas as emergent meta-properties of complex dynamic environments

The first major group of factors crucial for cooperation in public good dilemmas regards the situational context of individual decision-making. These factors mainly describe the structure of the social dilemma and aspects of its perception by individual actors. The basic understanding is that rather than "being" a social dilemma of some given structure, the situational context should be understood as a complex dynamic system which may under some circumstances and at some point in time provide behavioural incentives equivalent to the payoff structure of a social dilemma. Therefore, we argued that it is fruitful to conceptualise social dilemma structures as meta-properties emerging from the interaction of individuals with their external context on the one hand, and from the complex dynamics governing the temporal and spatial development of this context on the other hand. Individuals decide and act within the scope of this context and their actions in turn influence the future state of the context.

This notion was substantiated in the form of an abstract systems overview of the situational embeddedness of individual decision-making in a public good dilemma (cf. section 2.1.3 and the overview in Figure 2 on page 21). We argued that at least two structurally different sub contexts have to be considered: The environmental context provides boundary conditions that are physical in nature. Where is a public good provided and where do its benefits become accessible? How does the magnitude of the obtainable benefits vary in time and space? The second sub context represents the social embeddedness of individual decision-making like social networks, power relations, or group structure.

In general, the situational context is driven by complex dynamics which exist and develop independently of the public good provision. However, systems science states that in order to sustain its existence, a system coevolves with the environment. By a process of adaptation, a system reacts to fluctuations, dynamics, and structural changes of its environment. Therefore, in our context, a public good can be understood as a means to react to environmental challenges. In other words, a group of actors collectively adapts to its environment by providing a public (adaptation) good.

Individual decision-making in public good dilemmas is embedded simultaneously in both the social and the environmental sub contexts. Members of a providing group obtain a perceptual feedback from the social context (e.g. social influence or social norms) and from the environmental context (e.g. success of the public good provision or perceptions of other external conditions). In turn, actors process these local perceptions in order to derive actions to be forwarded to their environments.

6.1.3 Actor perspective: The HAPPenInGS theory

The second major group of factors critically influencing cooperation in public good dilemmas pertain to the intra-individual perspective of decision-making. This actor perspective is the scope of the second theoretical contribution of this thesis, namely the HAPPenInGS model of preference-guided action selection of individuals in public good dilemmas (cf. section 3.1 and the overview in Figure 5 on page 54). HAPPenInGS is specific in being grounded in the theoretic concepts and empirical results on social dilemmas and public goods, and psychological theory of decision-making. However, the model is kept generic and therefore independent of a specific case context.

HAPPenInGS represents actor heterogeneity as subjective preferences that guide individual decision-making. HAPPenInGS states that an individual's decision about his behaviour in the public good dilemma is based on a subjective appraisal of each of his investment options with respect his preference dimensions. HAPPenInGS covers three preference dimensions. Firstly, the attitude towards an investment option is represented in terms of the individual advantage the decision-maker associates with the respective behaviour, i.e. the expected subjective benefit of public good. As a second dimension, the expected conformity of an investment option with existing social norms is represented. This dimension covers the influence of injunctive social norms (Cialdini, Kallgren, & Reno, 1991). Finally, we represent social value orientations as a preference for a desired ratio between the decision-maker's contribution to the public good and the contributions of the other members of the providing group.

In HAPPenInGS the evaluation of the preference dimensions is based on an individual's perception of its situational context. The environmental sub context provides the decision-maker with local and subjective perceptions of the present state of the public good and of other (case-specific) non-social external factors relevant to the decision process. Behaviours that are put into action change the state of the environment. The actor perceives the consequences of his and collective behaviours as well as the generally varying temporal/spatial salience of the public good. This perception process constructs the actor's internal representation of the expected benefit of the public good. In its social context an individual perceives the investment behaviours of its social network peers and actively constructs an internal representation of the (present) social norm. Furthermore, the individual perceives the investment behaviours of other members of its providing group. This perception is not evaluated in a behavioural normative sense. Instead the individual compares the perception to its own investment behaviour and evaluates the situation with respect to its social value orientations.

The core formalisation of decision-making in HAPPenInGS is Ajzen's TPB with the extension of social value orientations, the latter being a well introduced concept in experimental social dilemma research. This embeddedness of HAPPenInGS in existing theory yields methodical implications which can fruitfully be exploited in the dynamic application of HAPPenInGS. These implications are incorporated into the main methodical contribution of the thesis which is recapped in the following subsection.

6.1.4 Methodical perspective: Agent-based modelling and simulation of social systems

ABSS is the method of choice to integrate both the actor perspective covered by the HAPPenInGS theory and the embedding in a dynamical systems context of public good provision. The main methodical contribution of the thesis is the abstract ABSS setup HAPPenInGS-A which is based on HAPPenInGS as the theoretical founding of agent decision-making (cf. section 3.2).

The basic principle addressed by HAPPenInGS-A is collective action for the provision of public goods. When do groups of heterogeneous individuals manage to provide a collectively desired good and when do they fail? The public good is assumed to emerge from the individual contributions made by members of the local agent groups on spatial extents of the environmental context. Agent collectives are implied by the position of individual agents in the environmental context. Agents located on the same patch belong to an agent group that collectively provides a local public good on the respective patch.

The behavioural target variable of an agent is the individual investment in the next time step of the model. Deliberative decision-making is modelled by an implementation of HAPPenInGS: Investment options are evaluated with respect to the subjective preferences of an agent yielding an expectation of the subjective utility associated with executing the behaviour. The selection of a behaviour is based on the comparison of the expected utilities associated with the behavioural options at an agent's disposal. In their social context, agents can perceive the behaviour of other agents in their group and the behaviour of agents in their simulated social network. These social perceptions enable agents to assess their subjective norm in the sense of the TPB and the conformity of the distribution of investments in their group with their social value orientations. Furthermore, agents perceive the level of the public good provided by their group. The perceptions are used in the utility calculation according to HAPPenInGS. The underlying notion of utility draws upon the multi-attribute-utility ("mental") calculations defined in the TPB. The subjective utility of an investment option may thus be understood as the strength of the intention to perform a given investment.

In outlining the setup of HAPPenInGS-A, we showed that the numerical tractability of the utility calculations underlying the TPB can be carried forward to the numerical implementation of HAPPenInGS. In principle, the TPB and likewise HAPPenInGS are static theories, i.e. they make "one-shot" predictions of behaviour from numerical utility calculations. However, HAPPenInGS can account for the temporal and collective dynamics of decision-making when integrated in an ABSS. In HAPPenInGS-A the dynamic feedback of an agent's behaviour to other constructs of HAPPenInGS is clearly represented. While past behaviours directly impact subsequent processes of *individual* utility updating, the feedback of an agent's subjective behaviour on the social norm perceived by other agents is a crucial driver of *collective* behavioural dynamics. In summary, while the focus of the HAPPenInGS theory is the *micro-level* of decision-making in public good dilemmas, the purpose of HAPPenInGS-A is to supplement the bottom-up *macro-level* perspective on public good provision by applying methods of ABSS. The particular understanding is that such macro-level properties do not exist per se; they rather emerge from complex micro-level processes and interactions, and can only be sufficiently described and analysed by the method of ABSS.

6.2 Simulation results and implications

6.2.1 Theory testing by theory simulation: HAPPenInGS-A

As it is typically the case for ABSS exercises, simulations with HAPPenInGS-A examine the micro-macro-link reflected in the interrelation of individual-level preference profiles in an agent population and macro-level outcomes. We tackled the question by exploring the range of implications of the HAPPenInGS theory through a series of simulation experiments (see section 3.3). In contrast to the case-specific simulation exercises which are recapped in the following two subsections the purpose of the simulation experiments with HAPPenInGS-A is not to make predictive statements for a particular application context. Rather, the simulation exercises draw on the implications of HAPPenInGS and its validation in a dynamical ABSS context.

By investigating the range of possible social value orientations in the scope of the HAPPenInGS theory it was confirmed that populations of agents which stress altruistic value orientations during decision-making are indeed successful in providing a public good while egoistic populations constantly fail. Moreover, simulations with HAPPenInGS-A allowed identifying transitions of collective behaviour in relation to different social orientation parameter combinations. As a conclusion, we stated suitable parameter settings for prototype preference profiles of altruistic, egoistic and neutrally oriented agents respectively. Whereas the first two types can be seen as HAPPenInGS counterparts of prosocials and proselfs as found in experimental work on public good dilemmas, the latter agent type characterises the transition range of parameters between the extreme parameterisations of the theory.

Subsequently, we investigated the interplay of social orientation and social conformity in HAPPenInGS-A and identified different facets of social coordination: Simulations indicate that high preferences for social conformity can override individual altruistic orientations, inhibit social mobilisation, and install a passive social norm that is collectively followed. In contrast, moderate preferences for social conformity yield high public good levels and in addition decrease the range of behaviours within the population. Furthermore, social conformity preferences reduce behavioural volatility on the individual level. Still, simulations indicate that such social adjustment takes time as mobilisation proceeds slower if agents strive for social conformity.

Finally, we investigated heterogeneous populations composed of different percentages of altruistic and egoistic agents. The main conclusion from these simulations with HAPPenInGS-A is that social influences decrease the inequality of behaviours between the altruistic and the egoistic subpopulations. As a result of social adjustment agents show behaviours that can deviate from their social preferences: Altruists tend to contribute less and egoists tend to contribute more when their social conformity preference increases.

The implications from the simulation analysis of HAPPenInGS-A have two components. Firstly, prototypic agent parameterisations were determined which are HAPPenInGS representations of three typical social value orientations also found in human subject experiments. In essence, this result links the circumstances found in the "virtual test lab" of HAPPenInGS-A to conceptions derived from real-world empirical evidence. In particular, the extracted prototype preference sets for three different agent types are vital for the instantiation of HAPPenInGS-A for a case study application context.

The second set of implications results from the dynamical analysis of the interplay of social conformity preferences and social orientations on the individual level, and the macro-level consequences. Some results mainly confirmed expectations and therefore demonstrated the consistency of HAPPenInGS: For instance, high preferences for social conformity might prevent social mobilisation even in predominantly altruistic populations. On the other hand it could be shown that medium social conformity preferences foster social mobilisation and in addition decrease inequalities of contributions on the individual level. In addition to the general plausibility of such results, they demonstrate the emergent complexity which arises from a simple and abstract theory like HAPPenInGS in the context of an ABSS exercise.

Other results of the analysis of HAPPenInGS-A were less intuitive: For example the assessment of the temporal dimension of social mobilisation showed that if agents strive for social conformity in addition to following altruistic preferences, the speed of social mobilisation is reduced. Clearly, the underlying process of inter-individual social adjustment demonstrates the interplay between individual value orientations and social norms in HAPPenInGS. However, neither the existence of the process as such nor its assessment can readily be guessed from the HAPPenInGS theory beforehand. Instead the results are genuine contributions of the methodical approach of ABSS.

Furthermore, the simulation experiments allowed narrowing down the circumstances under which social conformity preferences can conflict with social value orientations. Under such conditions individual behaviours may emerge to be inconsistent with individual value orientations – egoists contribute more, but in turn altruists contribute less. Again, such implications illustrate well the added value of the method of ABSS. Interestingly, there is empirical work demonstrating the existence of this "Boomerang Effect" for the case of household energy conservation (Schultz, Nolan, Cialdini, Goldstein, & Griskevicius, 2007). The study shows that when households are provided with a descriptive social norm (Cialdini et al., 1991) indicating average energy consumption behaviour within their residential neighbourhood they appear to adjust their consumption behaviour towards this norm. In other words, the social norm tends to interfere with other factors influencing decision-making. In line with the results of HAPPenInGS-A, the study showed that this adjustment symmetrical in nature: Households consuming more energy than the average reduce their consumption while those already saving energy increase their consumption towards the mean.

In the line of argument of the thesis HAPPenInGS and HAPPenInGS-A are vital elements because they transparently link theory and method development to the conclusions drawn from the literature review. This conceptual embeddedness is inherited by the case-specific instantiations of HAPPenInGS which are summarised in the following subsections of this chapter. Furthermore the common conceptual framework implies that the conclusions from the dynamic analysis of HAPPenInGS-A universally hold for these ABSS exercises. Therefore the insights from HAPPenInGS-A gain real-world relevance in the case specific discussion of results and in principle add to the set of cross-case implications (see section 6.3).

6.2.2 Theory application I: The case of neighbourhood support

The empirical background of the first real-world application case of HAPPenInGS is the domain of social mobilisation for neighbourhood support (cf. chapter 4). For the target region of Northern Hesse it is expected that in particular increased health care for older people is an important adaptation requirement under conditions of more frequently occurring heat waves caused by climate change. Public health service will likely not be able to provide the required comprehensive and area-wide health care. Therefore, neighbourhood help that supports elder people during heat waves is considered as an important local provider of the required care-taking activities. We showed that neighbourhood support is a public good which is provided by local groups of potential helpers in the locality they inhabit. Accordingly, decision-making of the potential helpers on their contribution to neighbourhood support is governed by a public good dilemma and may consequently be described by the HAPPenInGS theory.

The ABSS for the case of neighbourhood support is called HAPPenInGS-N. Like in HAPPenInGS-A, agents' decision-making in HAPPenInGS-N comprises a deliberative behavioural mode based on the HAPPenInGS theory, and exploration behaviour. In addition, behaviours which were repeatedly confirmed by deliberation can become habits for a given external context. In general, once habits are formed, agents simply repeat the respective behaviour without re-evaluating the situation by deliberation.

In addition to its theoretical embeddedness, HAPPenInGS-N is empirically linked to the case of neighbourhood support in Northern Hesse. The basic principle of this empirical embedding is to initialise simulations such that the agent population in HAPPenInGS-N reflects the socio-demographic characteristics found in the target region. This initialisation process makes use of large-scale empirical data of the lifestyle composition of urban neighbourhoods with reference to Sinus Milieus©. The rationale is (a) to represent lifestyles as agent types differing in their HAPPenInGS preferences, (b) to define neighbourhood groups as agent groups that reflect the lifestyle composition, size and spatial location found in the empirical data, and (c) to define a social network reflecting spatial closeness of the agents and the milieu properties of the agent types.

It is our point that HAPPenInGS-N's theoretical embedding in conjunction with the described empirical grounding contributes to the case-specific validity of the simulation results. We used the ABSS to assess the effect of different intervention scenarios aiming on the mobilisation of passive subpopulations. The basic assumption underlying the model representation of interventions is that measures like e.g. information campaigns make people rethink their behaviours. Therefore, in HAPPenInGS-N, agents which are the target of an intervention engage in deliberative decision-making despite possibly existing habits.

HAPPenInGS-N allowed observing how intervention campaigns impact the pathway of social mobilisation. Simulations showed that prevailing habits in a population may be replaced by new and more successful behavioural patterns which persist after the end of an intervention. The analysis of the simulation results allows scrutinising the different dimensions of such behavioural dynamics.

As a first dimension, HAPPenInGS-N facilitates the temporal assessment of the observed phase transitions of collective behaviours. This perspective enables a comparative assessment of the impact of different intervention strategies. As a result we found that comprehensive information campaigns that draw on the mobilisation of the full target population may be less successful than more focused campaigns that only mobilise population groups that fail to provide neighbourhood support. Secondly, the descriptive richness of the model enables a socio-behavioural impact assessment of the interventions. With respect to this dimension, simulations suggest that leading, traditional and mainstream lifestyles are sensitive to information campaigns and change behaviour whereas hedonistic lifestyles are rarely reached by the considered interventions. Thirdly, HAPPenInGS-N enables a spatial assessment of the interventions. In this evaluation context, simulations results point out regions with substantial potential for neighbourhood support and a small region where even comprehensive information campaigns show insignificant effect.

The simulation results motivate and support a number of case-specific policy recommendations. Firstly, simulation assessments suggest that information campaigns aiming at the full population may be less successful than selective campaigns focussing on specifically on unsuccessful subpopulations. Obviously, selective intervention is more efficient when relating the required mobilisation coverage to the achieved effect. Still, the modelled selective mobilisation is quite strict in assuming that unsuccessful neighbourhood groups may be identified dynamically at any point in time and accessed by a campaign.

Secondly, the socio-behavioural assessments suggest that, in order to achieve comprehensive social mobilisation, lifestyle-specific sensitivities to different measures have to be considered when shaping a specific intervention. Alternative intervention scenarios could comprise lifestyle specific interventions drawing on the fact that lifestyles differ in their communication channels and styles.

Finally, as a result of spatial analysis, simulations point out urban districts with lower potential for working neighbourhood support. This implies the suggestion that public health service should in particular monitor and support such hot spot regions during extreme weather events.

The investigated case of neighbourhood support frames a rarely investigated component of climate change adaptation which has only recently been discussed under the heading of "privately provided adaptation public goods and services" (Tompkins & Eakin, 2012). The defining feature of such goods is that they entail a public adaptation benefit which is generated by private adaptation action. This supports the hypothesis that individual climate change adaptation in general depends to a significant extent on individual volunteering activities that are often governed by social dilemmas. The open question is how far the common theoretical framework of social dilemmas along with case specific simulation exercises will carry towards generalizable theoretical insights on climate change adaptation.

6.2.3 Theory application II: The case of land reclamation

The empirical background of the second application of HAPPenInGS is provided by a case study located in the Odra river valley in Poland close to the border to Germany (cf. chapter 5). It focuses on those parts of the river catchment that are at risk of regular flooding in case of high water levels of the Odra. Experts propose that the negative effects of excess water stress could be mitigated (or possibly eliminated) by reinstalling a land reclamation system (LRS) that is neglected at present. To be effective the LRS requires regular maintenance. However, due to the fragmented land ownership in the Odra region there is usually a group of riparian landowners along an LRS channel who are each individually responsible for local maintenance of a channel section. Consequently, a maintained drainage channel of the LRS may in principle be conceptualised as a public good which is provided by the labour inputs of the riparian farmers. Therefore, farmer decision-making on whether to increase the quality of the overall LRS by cleaning their section of the channel system may be described by the HAPPenInGS theory.

The ABSS for the case of land reclamation is called SoNARe (Social Networks of Agents' Reclamation of land). The model's central agent type represents a typical small-scale farmer in the target region. Empirical research suggests that farmer decision-making on investing in LRS maintenance is driven by a mainly economic dimension considering the expected monetary benefits from a working LRS and the cost of its maintenance, and by a social-normative dimension reflecting social appraisal of LRS maintenance within the farmer community. The interplay of these two dimensions is explicitly represented in the case-specific setup of HAPPenInGS for the modelled farmer agents. The social context of decision-making is modelled within SoNARe as a simulated network of social influence between farmer agents. In contrast, the environmental context is represented by an independent hydro-agricultural simulation model of the effects of different weather conditions, LRS maintenance, and LRS neglect on each farmer's crop yields. The model is coupled to SoNARe and provides farmer agents with perceptions of the economic success of their farming activities.

In line with suggestions of local experts, SoNARe investigates a combination of two classical solution approaches to social dilemmas: Firstly, we include LRS initiator agents which are model representations of socially accepted lead personalities. In SoNARe the initiators' scope of action is restricted to the social context of collective decision-making. Initiator agents can approve or disapprove farmers depending on their behaviour by exerting influence through the ties of the common social network. Therefore, initiator agents actively influence the social-norm perceived by the farmer agents.

Finally, it is suspected that the sustainability of the farming system is largely influenced by the fact that farmers can claim and receive compensation payments in case of crop losses. To cover this aspect, SoNARe represents economic incentives in terms of compensation policies as a second solution concept. From the farmer perspective such payments influence the economic dimension of decision-making.

The integrated simulation model comprising SoNARe and the hydro-agricultural model was used to explore the impact of alternative compensation policies on mobilisation for collective LRS maintenance. Overall, simulations motivate that a reduction of compensation payments can further amplify the generally positive effect of socially active initiators and trigger a social lock-in in favour of LRS maintenance. However, the temporal pathways leading to such collective action differ with respect to the exact character of the simulated compensation policy. In this respect, simulations suggest that a complete cut-down of compensation payments indeed triggers a phase transition of behaviours from passive to collective LRS maintenance. But the course of this mobilisation process entails pronounced phases of economic stress for the farmers. Clearly, in real-life, farmers would abandon farming under such conditions. An alternative pathway of social mobilisation may be observed if compensation is paid selectively to LRS maintainers, which still significantly reduces overall compensation inputs compared to the status-quo situation in the target region. Under such conditions collective LRS maintenance is achieved while the economic stress of the farmer agents during the course of mobilisation is reduced. More interestingly, simulations point out that social mobilisation proceeds faster compared to the case of a full cut-down of compensation.

Even though the model is quite abstract it clearly demonstrates the interplay of individual economic drivers and social influence on one hand and external drivers set by climate and policy on the other hand. The comparative assessment of the modelled policy scenarios suggests that the presently passive farmer community in the target region can be mobilised by reducing compensation payments. Furthermore, simulations indicate that mobilisation can be accelerated if farmers contributing to LRS maintenance are selectively compensated in case of crop losses.

6.3 Overall conclusions and future perspectives

6.3.1 Simulating the process of social mobilisation: Solution concepts "at work"

It is the genuine purpose of the method of ABSS to describe the processes underlying collective social phenomena and to scrutinise their implications by simulation. In this respect, the abstract ABSS HAPPenInGS-A explored and validated the macro-level consequences of the HAPPenInGS theory. The case study simulations HAPPenInGS-N and SoNARe went a step further and investigated the effectiveness of typical solution approaches for public good dilemmas. In doing so, simulations start out from a model representation of the situation characteristics presently found in the respective case and explore possible futures by simulation. The initial conditions observed in both case studies correspond to a situation where public good provision is unsuccessful due to largely defective behaviour. The simulation experiments assess possible intervention scenarios which aim on changing the boundary conditions in the models systematically such that collective action may emerge. The results of such experiments contribute to the understanding of processes of social mobilisation in general and yield policy recommendations on promising intervention measures in particular.

The types of interventions investigated in the two case study exercises are diverse but they correspond to typical solution concepts for social dilemmas. The case of neighbourhood support considers information campaigns. The basic idea is that during information campaigns individuals actively refine their knowledge about useful behaviours in the dilemma situation. HAPPenInGS-N demonstrated when and how this individual-level process results in the emergence of new social norms, new habits and subsequently in collective action. The case of land reclamation investigates the effect of financial incentives. SoNARe showed that limited but focused distribution of incentives best fosters collective action.

Clearly, the types of solution approaches considered in HAPPenInGS-N and SoNARe match well the circumstances of the respective case. For the farmers in the Odra region financial considerations play an important role while the case of neighbourhood support focuses on voluntary behaviours which lack this economic dimension. However, the common conclusion for such HAPPenInGS models is that focused intervention is more effective that unselective intervention. This was shown for selective information campaigns in HAPPenInGS-N and for focused compensation payments in SoNARe. Apparently, the mode of providing incentives to a population influences the success of an intervention irrespective of the particular kind of incentive.

For the case of neighbourhood support simulations point out that passive behaviour of hedonistic lifestyles inhibits full mobilisation under the modelled information campaigns. However, there is some empirical evidence from an on-going survey that especially these lifestyles react sensitively to material incentives that reward contributing to neighbourhood support. As a conclusion, selective incentives which parallel information campaigns could be a promising approach to achieve comprehensive mobilisation. To this end further modelling exercises are required.

6.3.2 Empirical grounding

HAPPenInGS-N and SoNARe share a common theoretical embedding of individual decision-making in the HAPPenInGS theory which implies a strong similarity of the models in terms of the structures and processes they represent. However, the respective ABSS setups differ in the way they use either empirical data or assumptions to initialise structures and processes.

In HAPPenInGS-N, the agent population is set up from large-scale empirical data. This includes the initialisation of agent preference profiles, agents' spatial distribution, and social networks. In addition, a regional climate projection is used as external driver. However, empirical research which could be used to set up the production function of neighbourhood support was not available to the project. Therefore, the production function of the public good is largely based on assumptions derived from theory. Consequently, the induced dilemma structure is to an extent artificial and idealised in nature.

In contrast, due to the lack of available data, agent initialisation in SoNARe is largely based on assumptions. Nonetheless, the assumptions are non-arbitrary as they are at least qualitatively related to empirical observations. In contrast, the environmental context of agent decision-making is represented as a coupled hydro-agricultural simulation model of the situation characteristics in the target region. The analysis of the induced "real-world" social dilemma (cf. section 5.4.2) showed that incentives are not as "cleanly" in line with the game-theoretic conception of the incentive structure underlying HAPPenInGS-N. To this end, the case of land reclamation illustrates well our theoretical point that social dilemmas emerge from the complex dynamics governing the temporal and spatial development of the environmental context of individual decision-making and acting.

In particular for HAPPenInGS-N a step-wise refinement of the empirical grounding is a promising direction of future work. During the simulated time span external social drivers might gain importance. In the simulations agents "ageing" might become a relevant mechanism in order reflect demographic change in the region. This would feed back to the public good dilemma because the need for neighbourhood support should in turn increase. Likewise, the lifestyle distribution in the population changes over time which is not yet represented in the simulations. Finally, empirical founding can be further improved by including results of on-going surveys of the target area. This yet unexploited methodical link between model and survey data is further discussed in the following section.

In summary, both case-specific ABSS exercises have strengths and limitations in terms of their empirical soundness. Likewise, direct validation of simulation results is rarely feasible due to the lack of available datasets. To this end, we have to rely on domain experts to confirm that simulation results reasonably reflect the situation characteristics in the target area. All these points have to be transparently documented and clearly stated when simulation results and in particular policy implications are presented.

6.3.3 The potential of the methodical approach of HAPPenInGS

The three agent-based simulation models presented in this thesis are representatives of a particular paradigm within the multitude of existing approaches in ABSS. The thesis framed this school of modelling under the heading of psychologically sound middle-range models. The distinctive property of middle-range agent-based models is that they capture the observed individual and structural characteristics of a problem domain such that the model remains applicable to similarly structured cases. Such middle-range models obtain psychological soundness by grounding the model representation of individual decision-making adequately in psychological theory. In this respect, the models reported in this thesis are built around the HAPPenInGS theory. This particular setup has some notable methodical implications.

First of all, the grounding of agent decision-making in psychological theory ensures that all relevant drivers of behaviour and their interaction are consistently represented and therefore ensure the validity of a model's structure. Secondly, HAPPenInGS is sufficiently generic to remain transferable to simulation exercises for other empirical contexts involving a public good dilemma.

Finally, the fact that HAPPenInGS is embedded in the TPB and in theory on social value orientations links the class of HAPPenInGS models to a rich toolbox of instruments from empirical psychology: In principle, survey data from questionnaires for the TPB can be used for model initialisation or validation (Schwarz & Ernst, 2009). Likewise, empirical methods for measuring social value orientations can contribute to the empirical grounding of simulation models. In particular the latter implication of the methodical approach was not explored in this thesis and indicates promising follow-up research.

7 References

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Appendix

A substantial portion of the research reported in this thesis is based on computer simulations. Results were generated with three different simulation models: Chapter 3 presented HAPPenInGS-A which is the abstract ABSS implementation of the HAPPenInGS theory. Chapter 4 reported on the ABSS for the case of neighbourhood support, namely HAPPenInGS-N. Finally, chapter 5 presented SoNARe for the case of land reclamation in the Odra region. All three simulation model are grounded in a common theoretical and methodical approach. The setup of the models is documented in the respective subsections of the chapters. Likewise, the initialisation values of the most important model parameters are provided. This appendix reports on the respective technical implementation of the three models.

The full source code of each of the simulation models of this thesis and their technical documentation may be provided from the author. This appendix is to give an overview of the implementation and analysis environments of the models. For full details the reader has to consult to the corresponding files on the CD.

A. HAPPenInGS-A

HAPPenInGS-A was implemented in NetLogo version 4.1.3 (Wilensky, 1999). The NetLogo model file may be obtained from the author upon request. Documentation supplementing the details given in section 3.2 is included in the NetLogo model file.

All simulation results were generated with NetLogo's BehaviorSpace tool which is integrated with NetLogo. The tool allows performing structured sets of simulation experiments by varying the model input parameters. BehaviorSpace runs a model many times, systematically varying the model's input parameters (sometimes called parameter sweeping) and recording the results of each model run. The setups of the simulation experiments underlying the results of section 3.3 are stored with the NetLogo model file.

When performing simulation experiments with BehaviourSpace NetLogo dumps the results of the respective parameter sweeps to text files. The content of these files was compiled in a MySql database. Visualisations were done with R version 2.12.1 (R Development Core Team, 2010). The respective R scripts may be obtained from the author upon request.

B. HAPPenInGS-N

HAPPenInGS-N was implemented in Java in the Repast Simphony 1.2 framework (North, Howe, Collier, & Vos, 2007) which provides the modelling infrastructure including e.g. scheduling and data logging. Agent decision-making uses the Java library of the LARA framework (Lightweight Architecture for boundedly Rational Agents, Briegel et al., 2012).

The java source files of HAPPenInGS-N and the java class documentation is provided by the author upon request. HAPPenInGS-N requires a number of external java libraries. The respective jar files including LARA are may be obtained from the author. Additional java libraries are installed with Repast Simphony.

All simulations were conducted in the batch mode of Repast Simphony on a Linux system. The files required to perform batch runs may be obtained as a zip-archive from the author including all required java libraries. The model is run by executing *the* jar file in the Java Virtual Machine of the Linux system. Two command line parameters have to be specified: The Repast Simphony environment (folder *HAPPenInGS-N.rs* was used for all simulations) and the batch parameter file (see *batch_params_set_example.xml* as an example). Furthermore, various input dataset which are read during model initialisation are required (folder *data*). In addition, the Microm© dataset is read from a Mysql database. Due to copyright restrictions these data may not be distributed by the author.

Simulation results are logged to the MySql database. Visualisations were done with R version 2.12.1 (R Development Core Team, 2010). The respective R scripts may be obtained from the author upon request.

C. SonNARe

The overall model documented here consists of the main model named SoNARe and a coupled sub-model. This documentation focuses on the SoNARe model. SoNARe is coupled to a simple and abstracted hydro-agricultural model (Simple Hydro-Agricultural Model; SHAM) that reflects the main environmental characteristics of the target region. SHAM was developed at Wroclaw University of Technology and is documented in detail elsewhere (Holdys, 2007).

Technically, the SoNARe core model is a hybrid model. The modelling infrastructure (scheduling, data logging, visualisation, etc) is provided by the RePast agent programming framework version 3.1 (Recursive Porous Agent Simulation Toolkit, cf. North, Collier, & Vos, 2006). RePast provides the necessary functionality to interface with the model SHAM.

The java source files of SoNARe and the respective javadoc may be obtained as a zip-archive from the author including all required java libraries. SoNARe depends on some external java libraries. The respective jar files are found may be requested from the author. Additional java libraries are installed with Repast 3.1.

Simulation results are logged to the MySql database. Visualisations were done with R version 2.12.1 (R Development Core Team, 2010). The respective R scripts are provided by the author upon request.