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Analysis

A framework for mapping and comparing behavioural theories in models of social-ecological systems

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ABSTRACT

Formal models are commonly used in natural resource management (NRM) to study human-environment interactions and inform policy making. In the majority of applications, human behaviour is represented by the rational actor model despite growing empirical evidence of its shortcomings in NRM contexts. While the importance of accounting for the complexity of human behaviour is increasingly recognized, its integration into formal models remains a major challenge. The challenges are multiple: i) there exist many theories scattered across the social sciences, ii) most theories cover only a certain aspect of decision-making, iii) they vary in their degree of formalization, iv) causal mechanisms are often not specified. We provide a framework- MoHuB (Modelling Human Behavior) - to facilitate a broader inclusion of theories on human decision-making in formal NRM models. It serves as a tool and common language to describe, compare and communicate alternative theories. In doing so, we not only enhance understanding of commonalities and differences between theories, but take a first step towards tackling the challenges mentioned above. This approach may enable modellers to find and formalize relevant theories, and be more explicit and inclusive about theories of human decision making in the analysis of social-ecological systems.

1. Introduction

Formal models have been used extensively to study the interactions between humans and their environment, to advance theory as well as to inform policy making (e.g., Meadows et al., 1972; Clark, 1976; Nordhaus, 1994). In natural resource management (NRM), modelling has advanced our understanding of the dynamics of natural resources, their response to management interventions and environmental change, as well as their vulnerabilities and regenerative capacities. This has informed policy decisions on harvest quotas, agri-environmental schemes, the management of biological invasions, the location of biodiversity hotspots and corridors for inclusion in protection programs, and possible unintended side-effects of management interventions and policy options (Simberloff and Cox, 1987; Karagiannakos, 1996; Myers et al., 2000; Müller et al., 2011; Carrasco et al., 2012). However, because of the strong focus on understanding natural resource dynamics and their optimal management, human behaviours have been either neglected or oversimplified and remain a key uncertainty for sustainable management (Fulton et al., 2011).

Given that natural resource use systems are social-ecological systems (SES) in which humans shape and depend on their biophysical environment (Berkes and Folke, 1998), their adaptive responses to policy and environmental change cannot be neglected (e.g., Palmer and Smith, 2014). Modelling approaches need to explicitly combine ecological dynamics and human behaviour to address the interactions between the different domains. While a great deal has been achieved in conceptualizing the drivers, (co)evolution and implications of diverse

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human behaviour in natural resource management (Faber et al., 2002; Becker, 2006; Waring, 2010), integrating such conceptualization into formal models of natural resource use and management is still a major challenge (Janssen and Jager, 2000; Baumgärtner et al., 2008; Fulton et al., 2011; Milner-Gulland, 2012; Schlüter et al., 2012).

Common approaches for integrating human behaviour into formal models of social-ecological systems couple economic theory with resource dynamics (e.g., Clark, 1976; Nordhaus, 1994), capture human aggregated responses in feedback loops (e.g., Meadows et al., 1972), or use ad hoc assumptions (Smajgl and Barreteau, 2014). While the first of these is prescriptive in that it aims to determine the optimal resource management strategy or the optimal policy option given a set of constraints, the latter two aim to describe actual system dynamics by explicitly incorporating human behaviour. The first approach is often based on very simple assumptions about human decision-making, namely the concept of the selfish rational actor, also referred to as homo economicus. The frequent use of the rational actor in modelling human behaviour and decision-making in NRM is not surprising since it is the standard model in economic theory and is straightforward enough to include in mathematical formulations. This is perpetuated because theory building in economics often builds off a few well-established theories of human behaviour in order to allow for accumulation of knowledge. However, the key assumptions of the rational actor—that she has perfect knowledge and stable preferences, is selfish and makes calculations to identify an optimal decision that maximizes utility—are in contrast with empirical observations of how people actually make decisions concerning natural resource use (Siebenhuner, 2000; Van den Bergh et al., 2000; Hukkinen, 2014; Levine et al., 2015). Also, the assumption that these "deviations from optimal behaviour" can be considered as "noise", and hence would cancel out in large populations, does not hold because much of these deviations are systematic. For example, in real life people have cultural habits, learn from other people, and often obtain utility from interacting with and helping other people (e.g., see Fehr and Schmidt, 1999; Gintis, 2000; Fehr and Gintis, 2007). Such behavioural drivers and processes are expected to have consequences for the dynamics and performance of social-ecological systems at large.

The importance of including the relevant complexity of human behaviour in the study of human-environmental interactions has been alluded to in recent publications (e.g. Levine et al., 2015; Worldbank, 2015). The World Bank's report on "Mind, Society and Behaviour" (Worldbank, 2015) explicitly acknowledges the importance of capturing the most advanced understanding of how humans think and how context shapes thinking for the design and implementation of policies. Others argue that the current focus on a small set of theories of human decision-making in policy assessment (such as climate policy) limits the relevance of those exercises (Victor, 2015). Since formal models are used to inform policy making, the lack of inclusion of social science expertise can considerably limit both the usefulness of formal models and the effectiveness of policies.

There is an abundance of theories in the social sciences that describe and test how people behave in various contexts. For example, in social and cognitive psychology, research has focused on processes of decision-making (e.g., Todd et al., 2012), social influence (e.g. Cialdini and Goldstein, 2004), information processing (e.g., Anderson, 1990), time discounting (e.g., Hardisty et al., 2012), and reinforcement learning (Skinner, 1953), just to mention a few. Theories have been developed on the gains and losses of group decision-making and situational and procedural contexts that affect outcomes (for an overview see e.g., Kerr and Tindale, 2004). In behavioural economics, the focus is directed at heuristics and biases, prospect theory and the framing of decisions (see e.g., Kahneman, 2003; Venkatachalam, 2008). However, this impressive body of knowledge has barely found its way into the field of natural resource management in general, and social-ecological systems modelling of resource management contexts in particular.

Modellers who aim to introduce alternative theories on human behaviour and decision-making in their models of natural resource management face several challenges (see Section 2 for a more detailed discussion): (i) the vast array of theories on human decision-making, some of which are even competing, makes orientation in the field very difficult. Moreover, knowledge is fragmented across disciplines and disciplinary languages. Theories can have different foci, such as emphasizing the importance of selected social or environmental aspects. (ii) As a consequence, some theories on human decision-making address very detailed aspects of decision-making, while others are very broad and comprehensive. Modellers need to recognize this diversity in scope and aim, and may even need to combine several theories in order to model the process of human decision-making in a comprehensive way. (iii) The degree of formalization varies depending each theory's methodological roots (experimental, conceptual, empirical). Correspondingly, modellers will be required to specify the elements and/or processes embedded within theories to varying extents. (iv) Modelling social-ecological systems necessitates simulating systems over time, requiring the specification and representation of causalities in the models. Many theories on human decision-making tend to focus on correlations and thus lack an understanding of causal mechanisms that can be translated into a dynamic model. Modellers, thus, have to make assumptions about causalities when using such theories. Overall, these issues make the selection of relevant theories for natural resource management problems, their formalization in social-ecological models, and comparison with each other very challenging indeed.

This manuscript is a modest step towards providing a framework to facilitate the broader inclusion of knowledge on human decision-making into formal models of social-ecological systems. The aim of the framework is to support the identification and operationalization of alternative behavioural theories into formal models by providing and defining a set of concepts commonly found across different behavioural theories. Specifically, we aim to encourage modellers to think more systematically about the implementation of human decision-making in their models and make use of the diversity of human decision-making theories from the social sciences, where possible. We also intend to support experimental and empirical researchers in the behavioural sciences engage with a broader range of theoretical perspectives. The purpose of this framework is therefore threefold:

- to provide a tool and common language for mapping, describing, organizing, comparing and communicating theories of human decision-making, and by doing so
- to enhance understanding of commonalities and differences such that modellers can make informed choices on which theory is relevant for a given context and research question, and
- to support the operationalization of behavioural theories in formal models by providing guidance on relevant factors and processes of decision-making and facilitating a more systematic implementation

To provide a framework that meets these purposes is an ambitious goal. In order to make concrete progress, we narrowed down the type of decisions we focus on. Accordingly, we focus on resource users (representing individuals, households or villages) making decisions on when, where, how and how much to appropriate from a resource — these are decisions on what crop to plant, where to fish and how many trees to cut. We do not include, for now, higher-level collective choice decisions, such as changing institutional rules, but we do include decisions on compliance to rules and social norms.

The remainder of the paper is organized as follows: In Section 2, we discuss the challenges modellers face when formally modelling human behaviour. In Section 3, we introduce the framework *MoHuB* (*Mo*delling *Hu*man *Behaviour*) and apply it to a number of well- established social-science theories in Section 4. In Section 5, we discuss the framework and conclude by considering how we may use this framework to implement different theories in simulation models, compare them, and inform policy analysis.

2. The Challenges of Representing Human-decision Making in Social-Ecological Models

Modellers need to overcome a number of challenges if they want to include theories on human decision-making in their dynamic models. As outlined above, these relate to the need to navigate a vast array of theories scattered across many fields; to deal with different foci, levels of comprehensiveness and formalization; and, to assign causality even where causality is not well specified by a theory.

The first challenge is *finding relevant theories* and navigating the vast array of available theories and knowledge about human decision-making. Various social sciences (economics, psychology, anthropology, sociology, political science, etc.) study human behaviour in diverse and sometimes specialized contexts, using various theoretical approaches and terminology. In fact, each discipline or even sub-discipline experiences a range of alternative theories that aim to explain very specific aspects of human behaviour. For example, explaining why people cooperate in one-shot prisoner's dilemma experiments can depend on cultural factors, emotions, cognition, and neural or hormonal processes (Henrich et al., 2001; Hopfensitz and Reuben, 2009; Moll and Tomasello, 2007; Rilling et al., 2002; Eisenegger et al., 2011). This has led to many *specific theories* that relate to partial processes of human decision-making and behaviour, next to a few *generic* (overlapping) *theories*. The Theory of Planned Behaviour (Ajzen, 1991), for instance, is a more *generic theory* describing how behavioural beliefs and attitudes, normative beliefs and subjective norms, together with control beliefs lead to an intention to perform a behaviour and influence the actual execution of that behaviour. Hence, this theory describes a full process, ranging from the formation of beliefs towards the performance of behaviour. An example of a specific theory would be the Elaboration Likelihood Model (Petty and Cacioppo, 1984). This theory addresses the process of persuasion. It discriminates between central processing, where involved and capable people process arguments in shaping their beliefs, and a peripheral route, where less involved and less capable people evaluate cues - such as the attractiveness of the source - in shaping beliefs. This fragmentation of knowledge makes it challenging to unpack the implications of different theories, particularly in different contexts.

A second challenge is that, from a modeller's perspective, decision-making theories are often *not complete*. Formalizing a theory often uncovers logical gaps that must be filled in order to make a simulation work. Modellers need to make assumptions to fill such gaps (Sawyer, 2004). For example, when modelling human decision-making according to the Theory of Planned Behaviour (Ajzen, 1991), one needs to specify the subjective norm, which refers to an individual's perception about how significant others (e.g., parents, spouse, friends, teachers) would judge the behaviour under consideration. The theory does not specify what other agents are "significant others" nor what their level of significance is. Further still, the theory alone does not specify what principle should guide the formalization of the significance of other agents. Obviously, more specific theories can serve as a guide in this formalization, such as perspectives on interpersonal attraction. Variables can be identified (such as similarity, expertise, physical attractiveness, familiarity) that have an effect on who is considered to be a significant other, and, obviously, this differs among people, among situations, and over time, confronting the modeller with a vast, unlimited horizon. This requires that a modeller identifies the main drivers to be modelled, makes "crude assumptions" on the modelling details and then carefully checks the robustness of model results to these assumptions. These challenges are not unique to formalization of theories of human behaviour. In fact, most theories in the life and social sciences experience some ambiguities when translated into formal equations. This is in contrast to many theories in economics and physics that are described through mathematical equations.

The third challenge is *introducing causality*. Simulating human interactions with the environment over time requires the specification of causal relationships about how psychological, social and environmental factors influence an agent's decision-making. Many of the theories, however, do not specify causal mechanisms since they are based on empirical correlations and focus on the relationship between factors at one moment in time. Modellers thus need to make explicit assumptions on processes and mechanisms. A modeller who wants to model energy or alcohol consumption behaviour, for example, may have to make assumptions about how the provision of factual information about the actual behaviour of individuals within a community, such as the average energy consumption in a neighbourhood or the amount of alcoholic consumption in a student population, affects decision making (Cialdini and Goldstein, 2004). She thus has to specify functional forms on how information about the behaviour of others changes the likelihood of certain choices. This relationship can be explained in various ways, for example, by the fact that people want to conform to others or that the option that is dominant in the community becomes more salient. Ambiguities or lack of knowledge on how variables relate to each other and determine the development of the system over time, make it very important to be explicit about assumptions made and their implications for model results.

In sum, the challenge of modellers is to identify and transform relevant theories on human decision-making into crisp causal relationships, while the best available knowledge is fragmented, context dependent and descriptive. Given these challenges, it is no surprise that many models rely on rational choice, which is based on a clear, unified and well-established theory that has and can be easily formulated in mathematical equations. But rational choice theory does not represent our recent empirical knowledge on human decision-making. By providing a framework to communicate the knowledge from various relevant theories, we want to support a first step towards tackling these challenges and enabling the community to find, filter and formalize relevant theories. This will enable them to be more explicit and inclusive about the various theories of human decision-making in the analysis of social-ecological systems.

3. MoHuB - A Framework for Mapping and Comparing Behavioural Theories

We took an iterative approach in developing our framework. This approach involved formulating its elements, mapping theories and revising the formulation based on insights from: a review of reviews of human decision-making in natural resource management (Cooke et al., 2009; Meyfroidt, 2013; Scarlett et al., 2013; Van Vugt and Griskevicius, 2014) and in agent-based models (Carley and Newell, 1994; Bousquet and Le Page, 2004; Hare and Deadman, 2004; Matthews et al., 2007; Heckbert et al., 2010; An, 2012; Balke and Gilbert, 2014), as well as from experience with our own implementations of different decision-making models in agent-based models of natural resource management. Definitions given below for the components of the framework draw upon general definitions, e.g., given by the Merriam Webster dictionary, to avoid biasing the framework towards one specific scientific discipline.

A framework that supports communicating and comparing different theories of human decision-making needs to be generic enough to capture the majority of theories, and at the same time allow for a meaningful distinction between them. With this aim in mind, we decomposed the decision-making process within an individual into three major parts: 1) what comes in (perception), what goes out (behaviour) and what happens *in between* (i.e., rules' and representations that lead to the selection and execution of a behaviour) (Fig. 1). In Fig. 1, the outer box represents the *social and biophysical environment* and thereby the decision context of an individual. The individual herself (inner box) is represented by the structural elements (*state* and *perceived behavioural options*) and processes involved in decision-making. Decision-making involves both conscious and unconscious processes that lie at the

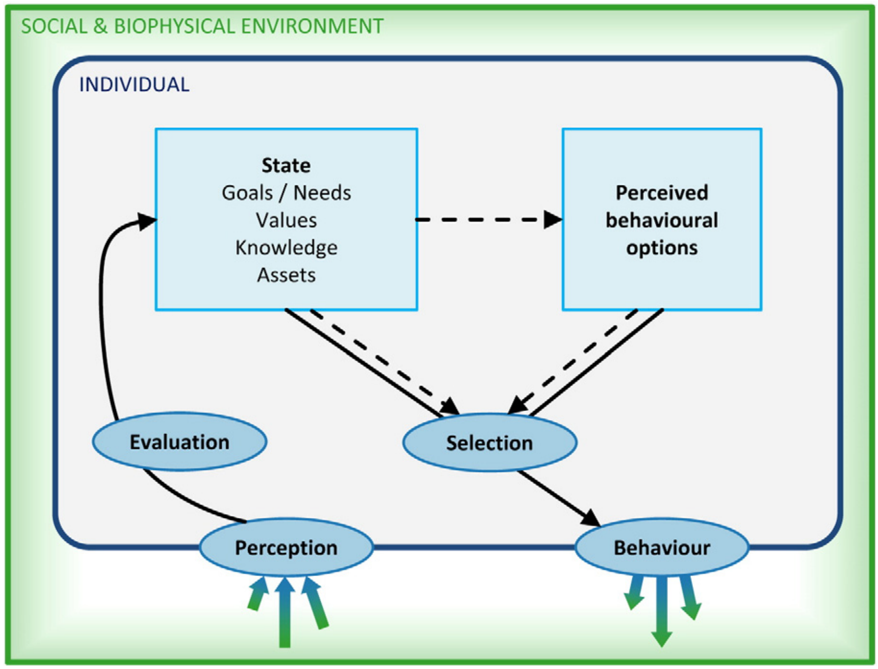

Fig. 1. The MoHuB framework of individual decision-making, allowing for the comparison of selected behavioural theories to model human behaviour. Solid arrows and corresponding ellipses indicate processes, boxes represent structural elements. Dashed arrows represent an influence of one element on another, e.g. the state influencing the set of perceived behavioural options.

interface of the individual and the environment (*perception* and *behaviour*) and internal processes (*evaluation* and *selection*). We argue that different theories of behaviour can be described as alternative configurations (presence and/or specification) of the structural elements, processes and context of an individual.

The seven elements that make up our framework are defined and further detailed in Table 1. They are connected through flows of information or processes that make up the decision-making process, as indicated by the solid arrows in Fig. 1. An agent perceives the state of its social and biophysical environment, evaluates the information and possibly updates its state. The state and the perceived behavioural options enter the selection process, where the behavioural option that fulfils given goals/needs/satisfaction criteria is identified. The behaviour is executed and affects the state of the social and biophysical environment. For simplicity, we focus on the main interactions between the elements, however, other ones are possible and likely. It is also important to note that not every theory includes or specifies all of the steps and that they do not necessarily follow this sequence.

The dashed arrows represent the influence of one element on another. The state of an agent for instance, may influence the perceived behavioural options, by either constraining an originally broader set of perceived behavioural options (e.g., due to limited available assets) or by enabling the agents to choose from additional behavioural options (e.g., due to new knowledge). The set of perceived behavioural options can also change over time as the result of learning, forgetting or changes in attention. Furthermore, the state may impact on the selection process by activating a different selection process (e.g. due to being dissatisfied). Finally, the perceived behavioural options may influence the search process regarding the search routines that can be executed on a given set (e.g., an optimization is not useful for a set with only one option).

4. Positioning Different Behavioural Theories in the Framework

We will now apply the framework to a selection of well-known theories of decision-making from different disciplines (Table 2). By doing so, we demonstrate its potential use and highlight how theories differ from each other, but also indicate challenges of mapping different theories. We selected the example theories from a set of ca. 30 theories with the aim to span a broad range of theories with respect to their application in different fields (economics, psychology) and their comprehensiveness in covering different drivers of human behaviour (individual, social, environmental). Rational choice theory and bounded rationality are theories widely used in natural resource management. Together with the Theory of Planned Behaviour and Prospect Theory they were the ones most often mentioned by more than 20 experts we consulted from various disciplines. Prospect theory is a rather specialized psychological theory about individual perceptions of gains and losses used in economics. Reinforcement learning is a behavioural theory of how very basic processes of reward shape future behaviour. The theory of planned behaviour is a comprehensive theory widely used in environmental psychology to explain pro-environmental behaviour. And, finally, the theory of descriptive norms focusses on the role of the social context. Note that this selection is not intended to be representative of the most important theories of human decision making in natural resource management nor is it comprehensive.

Table 2 provides an overview of the selected theories including their key assumptions and fields of application. For the mapping we went through the assumptions, concepts and relationships of each theory and the elements of the framework in an iterative way to relate a concept from the theory with a framework element. For example, we identified self-interest as a value of the homo economicus (state), maximum utility as its need (state) and optimization as the selection process (Fig. 2). When a theory specifies a certain element, the specific details of the theory, with respect to this element, are included in the figure. Elements that are not mentioned in the theory still remain in the mapping figure; however, they are faded out and do not include any details (e.g. evaluation in the rational actor model, Fig. 2).

In Box 1 we additionally provide a practical example of applying the different behavioural theories to a fisheries case in order to illustrate broadly how one would go about in designing agents that are based on the different behavioural theories.

Table 1
Definition and specifications of the different elements of the MoHub framework. Definitions are adapted from the Merriam Webster dictionary.

Element	Definition	Specification/examples
Context		
Social & biophysical environment	The environment the individual and her behaviour are embedded in	Social Env: actors and institutions[a] and their change over time that might affect individual decision-making through information exchange, coordination, observing what others do, satisfying need for belonging, need for fairness, etc. Actors' behaviour can affect the social environment, such as the social network, opinion dynamics, or collective processes. Biophysical Env: the biophysical properties and dynamics of elements such as a resource, a population or an ecosystem relevant for a particular decision context. Actors' behaviour can affect the amount, quality and location of a resource or population or the integrity of an ecosystem such as its food-web or habitat quality. The work of Ostrom (2005) provides helpful ways to define how the social and biophysical context may affect decision making,
Structural elements		
State	The internal state of an individual	Attributes of an individual that influence the behaviour selection process and possibly the perceived behavioural options. There are four classes of attributes: needs/goals, knowledge, assets, values
State: needs/goals	Physiological, psychological or material requirements for the well-being of an individual	Needs are motivational goals/factors for behaviour. Theories often include one or several of the following: utility, financial income, safety, reputation. Maslow developed a hierarchy of needs: physiological, safety, social, esteem and self-actualization needs (Maslow, 1943). Max-Neef classified subsistence, protection, affection, understanding, participation, leisure, creation, identity, freedom as basic human needs (Max-Neef, 1991).
State: knowledge	The information and understanding an individual has about her social-ecological environment and her own behaviour within this context	A) Declarative or factual: knowledge about the state and dynamics of the ecological system, the relation between actions and outcomes, memory of the outcomes of past actions or past system states; B) Procedural: knowledge about behaviours and the skills/abilities to perform; C) Relational: knowledge about the behaviour and opinions of other relevant actors, e.g. knowledge about other actors the individual knows and what they typically do
State: assets	Resources and other advantageous characteristics of an individual	A) Personal (e.g., skills), B) Social (e.g., social networks, trust); C) Financial assets. Note that knowledge or value aspects can also be considered assets in some theories.
State: values	Something (as a principle or quality) intrinsically valuable or desirable, i.e. not directly linked to the well-being of an individual or her motivational goals	Values reflect deep, slowly changing beliefs, e.g. a conservation value reflecting how an agent values the conservation of nature per se without any direct monetary benefits or the value of future benefits (discount rate). Note that depending on the context and on the theory, considering others could be either a need or a value. Similarly, preferences can be related to either values or needs.
Perceived behavioural options	The set of options the individual perceives and thus can choose from	The behaviours can be continuous, e.g. the amount of time an agent allocates between labor and leisure; or discrete, e.g. a set of behaviours the agent can choose from.
Processes		
Perception	The process by which an individual senses the surrounding social and biophysical environment	Complete: the individual receives all possible information from the environment that is relevant to a decision; or Incomplete: i.e., the individual does not receive all information and as such is bounded in her knowledge
Evaluation	The process by which an individual determines the significance, worth, or condition of the perceived state of the social and bio-physical environment	For example evaluation of the outcome of a past decision with respect to the returns provided, of fairness or equity of distribution of benefits within a group/society, or of the compliance with a social norm in the population.
Selection	The process by which an individual chooses her behaviour from the set of perceived behavioural options taking its state into account, resulting in the executed behaviour	Consists of either one or a multiple of different types of selection processes, e.g. • Random: randomly select one of the possible options • Optimization: evaluating all options and choosing the one with highest expected outcome • Satisficing: evaluating options until a behaviour is found that is expected to satisfy • Imitation: selecting the most popular behaviour of your friends, or larger community. • Social Comparison: evaluating options observed among others similar to you and selecting the one with the highest possible expected outcome. • Habitual (2 selection processes): 1. Automatic: (If satisfied) Repeating the behaviour performed earlier otherwise switch to 2. Deliberate: (If not satisfied) any other selection process to select, explore and evaluate another behaviour.
Behaviour	The behaviour that an individual executes as a result of the decision process	Behaviour impacts the socio-environmental system and, in addition to perception, is the second interface between an individual and its environment. Selected behaviours may fail to be executed if the behaviour is physically impossible.

[a] In the sense of formal and informal rules/norms.

4.1. Rational Choice Theory/Homo Economicus

When applying our framework to rational choice theory, the *state* reflects self-interested needs of the homo economicus, e.g. the goal to maximize a utility function, clear, stable and transitive values (or preferences), an individual skillset and complete knowledge about the social-ecological system (Fig. 2). The agent is aware of all *behavioural options* available to her and thus the "perceived" behavioural options include all possible options. The options are nevertheless still restricted by the agent's skillset or financial assets. We identify optimization as the

Table 2
Overview of the key assumptions and application fields of the six theories selected for mapping onto the MoHuB framework.

Theory	Origin/description	Key assumptions	Application Fields	Key references
Rational choice theory/Homo economicus	Economics	• Self-interested utility maximization • Goal-oriented • Stable and transitive preferences • Perfect knowledge • Unlimited cognitive capacity for calculating outcomes of all possible behavioural options	Economics Political science Psychology International relations Frequently used to model human decision making in natural resource use, e.g. tragedy of the commons or for environmental policy (Jager et al., 2000; Van den Bergh et al., 2000)	Simon (1978), Frank (1987), Monroe (2001)
Bounded Rationality	Economics, Psychology Rationality is limited by available information and cognitive capacity Note that there are many different versions of bounded rationality	• Goal-oriented, self-interested • May have cognitive limitations, incomplete or uncertain information about the world, and limited time • The behaviour choice can be realized through maximizing utility, reaching an aspiration level (satisficing) or following a heuristic (Gigerenzer and Selten, 2001)	Economics Psychology Political Science International relations Often used in agent-based models of natural resource management but not always explicitly referred to	Simon (1955), Gigerenzer and Selten (2001)
Theory of Planned Behaviour	Environmental Psychology Behaviour is mediated by intentions and perceived behavioural control Intentions are based on behavioural beliefs (attitudes), normative beliefs (subjective norm), and control beliefs (perceived behavioural control)	• Attitudes are aggregated beliefs about the strength of the effect of the behaviour (e.g., how important quotas are for conservation of fish stocks) and their normative value (e.g., whether conservation is bad or good) • Subjective norms are aggregates of the beliefs of approval/disapproval of the behaviour by important individuals or groups and the motivation to comply with important others • Perceived behavioural controls are aggregates of the beliefs about a control factor (e.g., money) and the perceived power of the control factor (e.g., is money important).	Environmental psychology Mostly applied in empirical studies to predict intention and behaviour Recently also applied in modelling studies to analyse the adoption of new practices or technologies (Schwarz and Ernst, 2009; Kiesling et al., 2012)	Ajzen (1991)
Habitual/ Reinforcement learning	Biology, Psychology Behavioural learning that originates in the classical (Pavlov, 1927) and operant (Skinner, 1953) conditioning theories Habit - "is a behaviour we do often, almost without thinking" (Graybiel, 2008, p. 359) Reinforcement learning is an approach to representing habitual behaviour	• Behaviour is initially deliberate and goal directed • If new behaviour is rewarded, the chances increase that it will be repeated • Repeatedly obtaining satisfactory rewards reinforces the behaviour • The selection of behaviour will be automatic as long as needs are satisfied • The actor will stop automatic behaviour and deliberate about alternative behaviours if need satisfaction drops below a critical level • If the reward devalues or disappears habitual behaviour persists at first, but will go extinct after longer absence of reward.	Psychology, Neuroscience Applied in the decision making of the Consumat approach as "repetition" under conditions of satisfaction and certainty, for example in farmer's behaviour (Van Duinen et al., 2015) Sometimes used in agent-based models of natural resource use to model experiential learning in simplified form (e.g. Schlüter and Pahl-Wostl, 2007) or based on artificial intelligence approaches (Lindkvist and Norberg, 2014)	Pavlov (1927), Skinner (1953), Graybiel (2008)
Descriptive Norm	Social norms are studied within different social science disciplines as a key element affecting decision-making A distinction is made between descriptive (influence of perceiving what other people do) versus injunctive norms (a person's perception about socially acceptable behaviour) (Cialdini et al., 1990)	• Observing the behaviour of others can have an impact on a person's behaviour • Observation can take place in an almost subconscious manner, during which the observed behaviour becomes more salient for selection • Or the observation can be more deliberately processed, such that other people's behaviour serves as a cue in deciding the proper action to take in a particular situation	(Experimental) studies of environmentally related behaviour, such as littering (Cialdini, 2003), reuse of towels in hotels (Goldstein et al., 2008), voting behaviour (Gerber and Rogers, 2009) and energy use (Schultz et al., 2007). Except for the work of Feola and Binder (2010) the authors do not know of the explicit use of descriptive norms in models of social-ecological systems	Cialdini et al. (1990)
Prospect Theory	Psychology Introduces important aspects from cognitive psychology to the rational actor model, specifically with respect to how people's willingness to seek or avoid risk influences their decisions	• Actors bias a rational decision because the context (social or physical setting of a decision situation) shapes their aversion to risk • Actors have a degree of risk aversion, whereby actors bias decisions towards avoiding loss over chancing a gain (Hastie and Dawes, 2001) • When the stakes are small, actors tend to "gamble" and seek more risk (Lefebvre et al., 2010)	International relations (Goldgeier and Tetlock, 2001; Levy, 1992); Environmental management (Bartczak et al., 2015); Financial risk management (Fiegenbaum, 1990); Insurance markets (Sydnor, 2010) Recently the theory has been applied to problems related to NRM in variable environments (Rajagopalan et al., 2009)	Kahneman and Tversky (1979)

selection process of the homo economicus model. When optimizing, a selfish homo economicus selects the behavioural option that maximizes her utility, given the possible costs and constraints. Since the rational agent is "all-knowing", with unrestricted cognitive capacity, she is always able to calculate and select the optimal option. Her *behaviour* affects the social-ecological system. If the rational actor considers future states of the system in her decision (she has perfect knowledge about future outcomes of her actions), any actual feedback from the system does not carry any information that is new for this actor (hence there is no perception or evaluation). However, in some cases, a rational

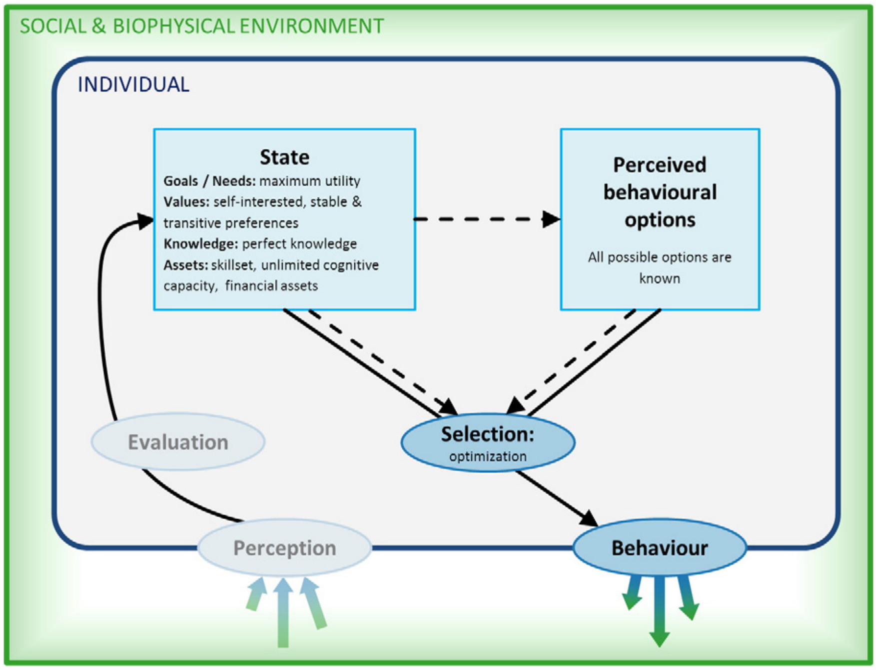

Fig. 2. The rational actor mapped to the MoHuB framework.

actor can be modelled with complete information only about outcomes of current actions and therefore, would need to perceive additional information from the system in order to decide on behaviour during the next time step. The perception of the rational actor is not restricted by cognitive capacity, and she is fully aware of her impacts on the system and payoffs resulting from her actions.

4.2. Bounded Rationality

Bounded rationality can be represented within the framework as a modification of rational choice theory (Fig. 3). Note that there are many different versions of bounded rationality with respect to how limited information, the kind of information and cognitive capacity affects decision making. The selection process of a boundedly rational actor can be optimization but also satisficing, the use of heuristics or others. When mapping bounded rationality onto the framework limited perception is an important element, contrary to homo economicus. Limited perception of the social-ecological environment may affect the available information and knowledge in the state of the agent, the perceived behavioural options and ultimately the selection process. Cognitive limitations may also directly affect the selection process leading to satisficing behaviour, i.e. finding the (first) behaviour that satisfies a need, or the use of heuristics. When evaluating new information, a boundedly rational agent may adjust preferences, gain new knowledge or update and learn heuristics.

4.3. Theory of Planned Behaviour

When mapping the theory on our framework, attitudes, subjective norms and perceived behavioural control are placed in the state (Fig. 4). Attitudes relate to the knowledge (belief of the effect and its strength) and values or needs (evaluation, e.g., good or bad). The subjective norm relates to the knowledge of the agent (beliefs about the approval or disapproval of the respective behaviour by others and their importance for the agent). The control factors correspond to the assets, while the perceived power of a control factor is part of the knowledge. Attitudes, subjective norms and perceived behavioural control act as a filter that determines the intentions for the different perceived behavioural options. The selection process is a function (which needs to be specified by the modeller) that links behavioural options to performed behaviour, mediated by the perceived behavioural control. Options that have a higher intention and that are perceived as being in the control of the actor are more likely to get executed by the agent.

4.4. Habitual Behaviour/Reinforcement Learning

Theories on habits/reinforcement learning are - in contrast to many other theories - explicitly incorporating feedback, i.e., the positive outcomes of performed behaviour result in reinforcement of this behaviour in a next time-step. Positive and negative experiences (history) are reflected in the habit formation by being stored in the state (knowledge) and determine the chance of a behaviour being selected again. Negative experiences result in avoidance, and hence potential improvements of behavioural outcomes are not noticed via direct reinforcements. As long as positive reinforcements are being experienced at regular intervals, this positive feedback-loop will sustain the cycle of performing behaviour – experiencing positive reinforcement. As soon as a habit is formed, only more cognitive processing (reasoning) may result in reconsidering a behaviour. This circularity is an essential component of habitual/reinforcement learning.

When mapping the key concepts of reinforcement learning onto the framework, the importance of cyclical processes of behaviour and rewards is reflected in the focus on the selection (of behaviour) and evaluation (reward) processes (Fig. 5). The two alternative decision making modes included in the theory, automatic versus deliberate, are represented as two alternative selection processes. The selection of the process depends on the actors need satisfaction which is part of the state of the agent (needs). The script that defines the behaviour to perform under the automatic selection process is part of the agent's knowledge. A script can address a single behaviour-outcome link (e.g., irrigating when the soil is dry), but also, more complicated structures of behaviour-outcome relations are possible (e.g., a farmer may have a repertoire of habitual responses to different conditions of weather, season and state of the crop). The performance of a behaviour is evaluated concerning the satisfaction of different needs (*evaluation*). When agents repeatedly go through the cycle, from perception and evaluation to behaviour, choices that satisfy are reinforced. The more often new behaviour is being performed, and the more consistent the person experiences reinforcement, the stronger the script gets, and the more stable/strong the new habitual behaviour becomes.

When no reinforcement follows after performing the habit, after some time the need satisfaction will drop below a certain critical level (e.g., linked to the person's ambition level), causing the person to switch towards deliberating about alternative behaviours. For example, one or a few times fishing with a very disappointing catch is not likely to change the behaviour of a fisher. However, after a few instances the fisher will start thinking about possible causes and alternative behaviours. This deliberation will also include the longer-term outcomes and goals, which are not being considered while in automatic mode. Note that the habitual/reinforcement learning does not specify the deliberative processes when a habit is being reconsidered. Here, different theories can be applied depending on the context of deliberation, such as the other theories addressed in this paper (i.e.: the rational actor, prospect theory, theory of planned behaviour or descriptive norms).

4.5. Descriptive Norm

When placing the descriptive norm within the framework we can directly relate it to perception and behaviour options, and observe how it affects behaviour through the decision-making process by making the dominant behaviour of others more salient (Fig. 6). Perception is the process of observing the actions of others, either by direct information or by receiving information on other people's behaviour. People learn the descriptive norm based on repeated observations (Kashima et al., 2013). During the evaluation, the observations of the behaviours of others are evaluated and the dominant behaviour of others is determined. This makes it more likely that this dominant behaviour is selected because people often value conformism. *Values* within the state component are important in understanding how a person may react to a descriptive norm. Here, a distinction can be made between conformism, non-conformism and *anti*-conformism (see e.g. Levine and Hogg, 2009). A non-conformist is not much affected by the observed behaviour of other people in contrast to the conformist and anti-conformist. Here, the conformist is likely to comply to the group behaviour, and the anti-conformist wants to deviate from the group behaviour. The perceived dominant behaviour of others influences the saliency (activation) of the perceived behavioural options. Also, following the majority behaviour can result in a higher social need satisfaction in the state for conformists, and a lower social need satisfaction for anti-conformists. The dominant behaviour becomes more salient for those who are more socially susceptible, and is therefore more likely to be selected by conformists, and less likely by anti-conformists.

4.6. Prospect Theory

When mapping prospect theory onto the framework, much emphasis is put on the evaluation process as this is where the probability of events is evaluated, as well as the values of an agent such as its risk attitude (Fig. 7). In the context of prospect theory people *evaluate* possible future outcomes differently based on the probability of the events. Each of these events occurs with a certain probability that may, or may not, be *perceived* by the decision-maker. Commonly, people underestimate chances of rare events eventuating, for example extreme storms that have a probability of occurring once every 100 years. In contrast, people can overestimate the implication of such rare events. An example is the perceived risks from Ebola virus vs. influenza in the USA. While an Ebola case occurs with much less probability people tend to weigh the risks more heavily and this may influence the expected value of the possible actions.

Furthermore, people's values play a major role in defining the perceived behavioural options. Agents' attitude towards risky behaviour will weigh gains and losses differently, but just how will depend both on the person, and how large the potential loses or gains are. What defines a loss vs. a gain is a threshold, or more precisely, a reference point that is a reflection of people's expectations or beliefs about past outcomes. It is important to note that the function that defines the risk attitude can represent different types of behaviour, such as risk aversion, relentless or indifference to the perceived risk (Wakker, 2010).

While a range of factors influence how an individual weighs loses and gains, in a modelling context, once the total value function for

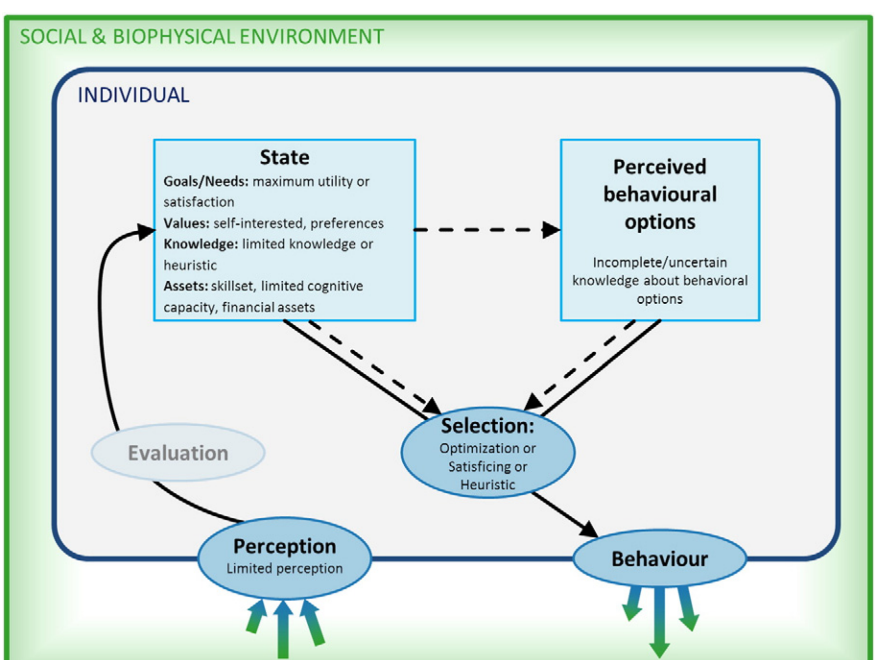

Fig. 3. Bounded rationality mapped to the MoHuB framework.

Box 1
A practical example of applying the different behavioural theories to a fisheries case.

Fisheries are a classical example of a common pool resource where individual resource users take decisions about how to fish (e.g. which gear), where to fish, at what time and for how long (e.g. how much time/effort to spend at sea). We use this example to illustrate the application of the six theories in an agent-based model of a fishery based on their mapping in the MoHuB framework. Note that implementations of the six theories in models of social-ecological systems for rangelands, fisheries and dryland agriculture are currently under development.

A *rational actor fisher agent* (homo economicus) in this fishery model would calculate the expected utility (e.g. net benefit from fishing) of all behavioural options available to it (of which it has complete knowledge and skills to execute) at every time step. It then selects the option that provides it with the highest utility. When calculating the expected utility it has perfect knowledge of the dynamics of the fish population, costs and prices, as well as the behaviour of all other actors (or he assumes that they behave in the same way as itself).

The *bounded rational fisher agent* could be implemented in many different ways as the theory only addresses the aspect of information availability and how information is processed by the agent, but does not prescribe for instance any selection process or goals or values. The agent thus could also engage in a process of finding the behavioural option that maximizes its utility, but with the knowledge about the state of the resource, the market or others' behaviour that is available to it. It could, however, also engage in satisficing behaviour and select the first behavioural option that satisfies his needs (even if another one that he has not evaluated yet would provide him with higher utility), reflecting constraints on the cognitive capacity of the agent.

A fisher agent that behaves according to the *theory of planned behaviour* would have a set of attributes reflecting its beliefs about the effect of fishing on its own well-being and the state of the fish population, and values about those states (e.g. whether an overharvested fish population is bad for it or others). He would have knowledge about the approval or disapproval of his fishing actions by other fishers and value them as to their importance for his decision. Finally the agent would know what it can control and whether that factor actually influences the state of the fish population or other aspects it is concerned about. These beliefs, values and constraints all influence the formation of its intentions, which may then be executed as a behaviour if he believes that it will lead to the desired outcomes. However, the way how these factors form intentions for different behavioural options and how a behaviour with a desired intention is selected (i.e. the selection process itself), is not specified by the theory and thus needs to be specified by the modeller.

A *habitual fisher agent* has a need, e.g. a certain amount of fish required for its well-being. It executes a behaviour, e.g. will go fishing with a certain gear, at a specific time, to a specific place and for a specific amount of time, based on his knowledge of the link between the behaviour and its outcome (a script), as long as the net returns it gets from this behaviour satisfies its needs. Every time step that it brings back a catch and its needs are satisfied the behaviour becomes stronger and the threshold to switch to a different behaviour becomes higher. If the satisfaction drops below a threshold the agent will start deliberating about alternative behaviour. The theory does not specify how this deliberation takes place.

A fisher agent that follows a *descriptive norm* will observe the behaviour of others, e.g. where they go fishing or what gear they use, and evaluate his observations in order to identify the dominant behaviour in the observed group. Its perception of the dominant behaviour will make this behaviour more salient for the agent. Whether it will follow it will depend, however, on two factors: first, its social susceptibility, i.e. whether it wants to conform to the dominant behaviour, ignore it, or deviate from it , and second, its social need, which will be more satisfied if he follows the behaviour of the majority, and lower if it deviates from it.

A fisher agent that behaves according to *prospect theory* will behave in order to maximize its own utility, similarly to the rational actor fisher, but will additionally weight expected gains or losses depending on its risk attitude. This means agents will evaluate the probability of, for instance, a low catch or a bad weather event that may prevent it from fishing. How fishers perceive losses or a gains depends on a reference point, for example a risk averse fisher may seek risk when the stakes are low compared to past catches (i.e. gambling - where agents value potential gains more than the possibility of losing).

each behavioural option can be defined, the selection of behaviour is thereafter based on selecting the optimal return, and hence, prospect theory can be operationalized as a specialized version of the rational actor model.

4.7. Summary of Mapping of all Theories on Framework

Table 3 summarizes the main attributes of the different theories as identified from the mapping process.

5. Discussion

Managing natural resources is managing people, as the behaviour of resource users is a key factor for successful management (Hilborn, 2007; Fulton et al., 2011). Despite the widespread recognition of the importance of complex human behaviour for sustainable resource management, many formal models are still based on the over-simplifying assumptions of the rational actor. This is particularly critical when models are used for real world policy support where humans may behave very differently than assumed. Empirical and experimental research in psychology, behavioural economics, sociology, or anthropology on the other hand, has developed many alternative theories of human behaviour. We argue that this gap between the representations of human behaviour in formal models and the rich evidence of the nuances of human decision-making in the real world is, to some extent, due to the plethora of theories developed scattered within and among the different disciplines (some of which are generic while others are very specific), the different terminologies used in different fields, and the lack of understanding of causal mechanisms that explain how factors interact over time in determining decisions and behaviours. When implementing a behavioural theory in a formal model, a modeller thus faces the challenge of identifying a relevant theory, potentially dealing with incompleteness in the representation of the decision-making process, and the lack of specification of causal relationships.

In this paper, we proposed a framework for operationalizing theories of human decision-making in natural resource management contexts to tackle some of these challenges. The framework supports mapping, describing, organizing and comparing different behavioural theories as a first step towards choosing and implementing them in formal models of social-ecological systems. Each theory uses a vocabulary that is specific to the discipline it belongs to. Our framework provides a generic

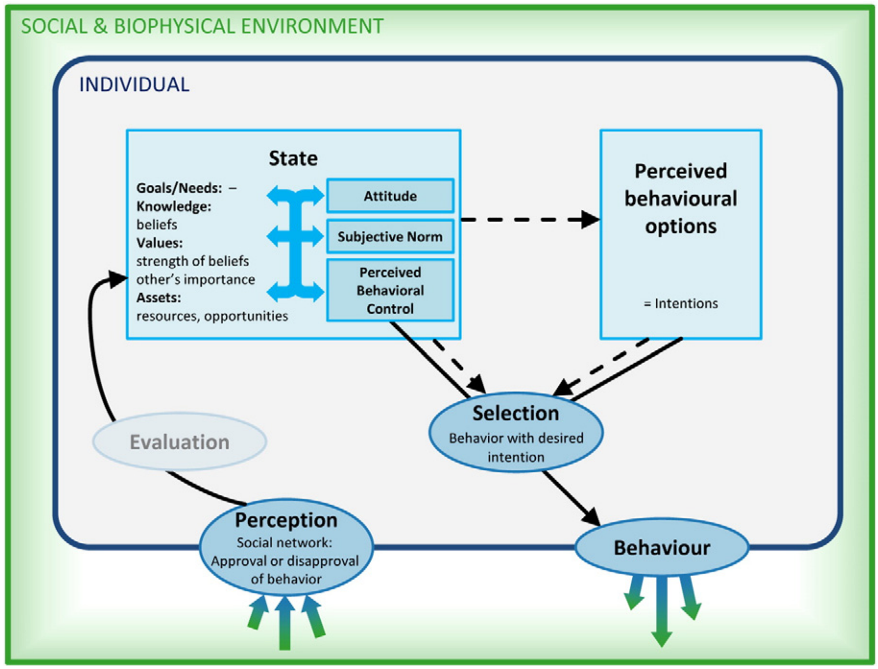

Fig. 4. Theory of planned behaviour mapped to the MoHuB framework.

language that can be used to describe multiple theories using the seven elements of the framework – social and biophysical context, perception, evaluation, state, perceived behavioural options, selection process, and behaviour. This facilitates mapping and comparison of different theories with respect to their structure and dynamics and their implications for understanding natural resource management. Furthermore, it can be used to communicate how a theory was formalized to implement it into an agent-based model. We do not claim that the framework can capture all theories of human decision-making in a natural resource use context. As a first step we hope it will be useful to capture many relevant theories and in the long run, supports a broader inclusion of these theories in social-ecological models.

5.1. Mapping Theories to Clarify their Focus and Underlying Assumptions

Our experience with the mapping of the six selected theories showed that it was possible - with a bit of flexibility in the interpretation of the elements - to map each theory onto the elements. The comprehensive process of specifying the elements of a behavioural theory facilitates communication about the assumptions of the theory, and can help clarify the meaning of the diversity of concepts used in different theories. It also makes explicit the focus of a theory, e.g. which of the elements are considered important determinants of behaviour (Table 4 – "Focus"). The mapping highlights which ones are represented and which ones not, how they are represented, and how they may

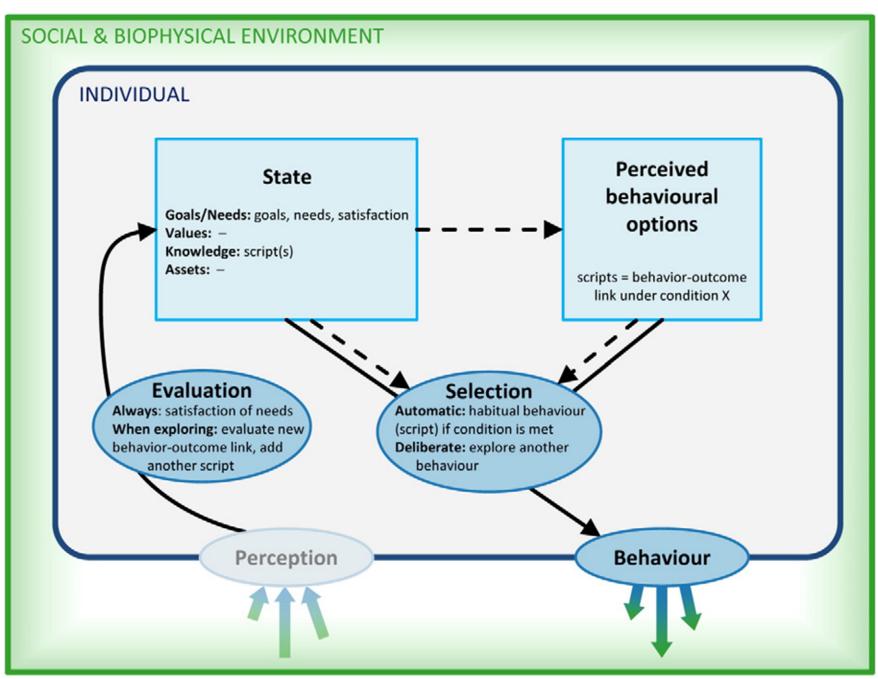

Fig. 5. Habitual Decision-making/Reinforcement learning (psychology) mapped to the MoHuB framework.

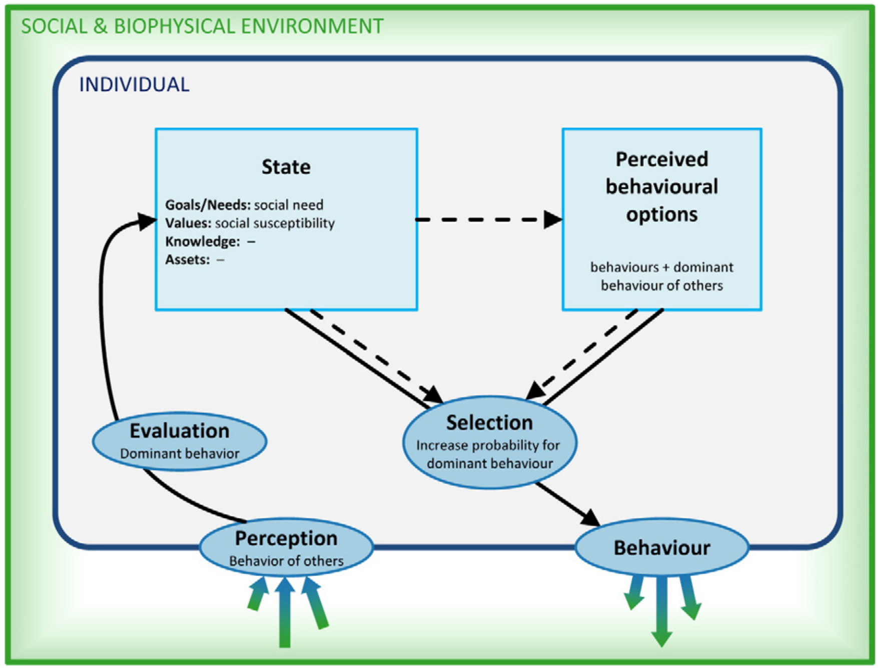

Fig. 6. Descriptive norm mapped to the MoHuB framework.

interact over time to determine the behaviour of the actor. As such, it can facilitate the identification of commonalities and differences between theories. For instance, a theory may focus on the role of actor characteristics (state), the options an actor can choose from (perceived behavioural options), or the way she makes her choices (selection process). For instance, our mapping of the rational actor clearly shows that, in this theory, actors maximize their needs (e.g. expected utility) by exploring all available options. In contrast, in the descriptive norm theory, decisions are almost exclusively influenced by the perception of the behaviour of others in the social environment. In some theories, the needs and goals of the actor are driving a decision (e.g., bounded rationality, prospect theory) while others don't specify any needs and goals (e.g. theory of planned behaviour, descriptive norm). The theory of planned behaviour is very specific on the elements of the state of an agent, such as its attitudes, subjective norm and perceived behavioural control, even specifying the components that determine its value. Yet it remains very unspecific on the actual selection process that selects among different intentions.

The mapping also reveals where a theory lacks detail or relevant information on particular aspects of the decision-making processes needed to implement it in a formal model (Table 2 – "degree of completeness"). In the rational actor model, for instance, changes of behaviour over time are not made explicit, i.e., the informational feedback from the social and biophysical environment is not specified. In the theory of planned behaviour

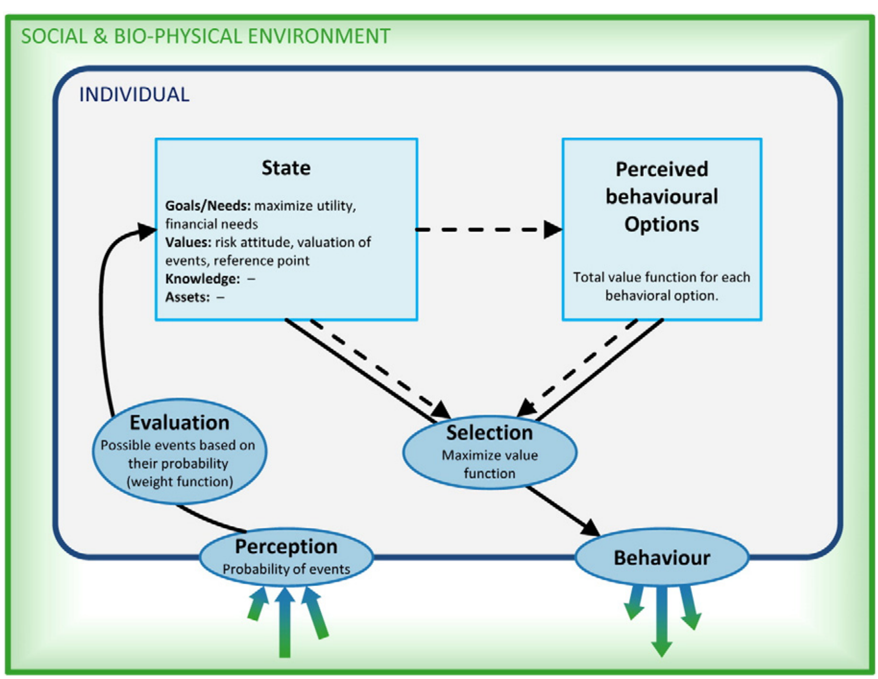

Fig. 7. Prospect theory mapped to the MoHuB framework.

Table 3
Summary of the mapping of the theories.

Theory	Perception	Evaluation	Selection	State	Perceived behavioural options
Rational actor	All information needed for decision available	Not specified	Optimization	Self-interest/utility/ preferences	All are known
Bounded rationality	Constrained by cognitive capability or bio-physical reality	Can include learning	Optimization Satisficing Heuristics	Preferences	Limited knowledge about available options
Prospect Theory	Probabilities of events	Weighting of different possible outcomes	Optimization	Risk attitude reference point	Filtered by risk perception and attitude
Theory of Planned Behaviour	Social network	Approval/disapproval of behaviour by others	Intention with highest value becomes most important	Beliefs, strength of beliefs, others' importance, resources, opportunities	Intentions
Descriptive Norm	Behaviour of others	Dominant behaviour	Dominant behaviour becomes more salient	Social need Social susceptibility	Behaviours and dominant behaviours of others
Habitual/reinforcement learning	Not specified	Need satisfaction	Automatic or deliberate	Needs Scripts	Scripts

all components of attitudes, subjective norms and perceived behavioural control could possibly change over time if aspects of that are perceived and evaluated dynamically. However, the theory itself does not state so. For a boundedly rational actor the selection process is not specified, rather, several processes may be used. The habitual/reinforcement learning theory does not describe how an agent decides deliberately when it explores a new behaviour. Gaps in a theory may, however, open up opportunities to link with other theories that specify missing process. One could combine the habitual model with the descriptive norms model to represent deliberate decision-making such that an agent follows the norm when it explores and carries out its habitual behaviour when it is in an automated mode. The framework can thus facilitate a process of integrating different theoretical perspectives.

5.2. Limitations of the Framework

Our mapping of the theories revealed some limitations of the framework. Our framework does not neatly capture processes that go beyond a single time step, such as learning. This becomes particularly problematic when the decision of an agent depends on the decision- making process in the previous time step, such as in the case of the habitual model. Here, the decision of an agent to explore new behaviour can only happen when it did not receive positive reinforcement after repeatedly performing the habit. Hence, processes related to learning and habitual behaviour can only be understood in terms of repeatedly running through the framework cycle. The dynamics of behaviour and behavioural change are a result of iterations of the decision- making processes over time (i.e., running the model). For example, learning emerges as a change in selected variables of the state such as knowledge or values or as a change in the behavioural options resulting from new information or the observation of the behaviours of others (social learning).

The framework also does not specify the elements of the social and biophysical environment or their change over time, such as rule changes or resource growth that may influence agents' decision making. Rules jointly developed by resource users for instance have proven to be an important factor for sustainable natural resource use in common-pool resource dilemmas by constraining individual self-interested overharvesting (Ostrom, 2005). Most of the theories considered here include elements of the social or biophysical environment in the decision making process such as the behaviour of others in the descriptive norm or environmental variability in prospect theory. They were mapped on to the perception element which links the social and biophysical environment with decision making. The framework, however, does not include how these contextual factors change (e.g. through rule-making processes or growth of a resource stock).

For some theories, it was difficult to map specific terms of a theory onto the framework vocabulary. In general, flexibility is required to relate a theory-specific concept to the concepts of the framework. The term "preferences", for instance, could be mapped as needs and goals or values depending on the theory or application context. The concept "intentions", from the theory of planned behaviour, does not have a direct equivalent in the framework. It also does not specify whether the intention with the highest values is always executed. When mapping, and later, when implementing a theory in a formal model, the modeller has to make many assumptions on causal relationships, particularly when the theory is based on correlations, as in the case of the theory of planned behaviour. Finally, as the framework focusses on individual decision-making, it cannot deal with processes or theories that include group or collective decision-making.

Table 4
Assessment of the different theories with respect to their use in formal modelling of SES.

Theory	Focus (element(s) of the framework that is/are most important)	Degree of formalization	Degree of completeness (are all elements described)	Representation of dynamics	Frequency of use in models of natural resource management
Rational actor	Goal-oriented *needs* optimization (*selection*)	High (equations)	Medium	No	High
Bounded rationality	Imperfect *perception* and *selection*	Medium (no equations given, but clearly described)	High	No	High
Prospect Theory	(*E*)*valuation* of the probability of different events	High (equations)	Medium	No	Medium
Theory of Planned Behaviour	Elements of the *state* that determine intentions	Medium	High	No	Low
Descriptive Norms	*Perception* of the behaviour of others and *evaluation* of dominant one	Low	High	No	Low
Habitual/Reinforcement Learning	Two different types of *selection processes* (automatic versus deliberative)	Low	Medium	Yes	Low

5.3. Operationalizing Behavioural Theories in SES Models

A comparison of the six theories analyzed here revealed their strengths and weaknesses with respect to the elements of decision-making that are well represented and those that are missing. Table 4 summarizes an assessment of the different theories with respect to additional criteria that may be relevant for the choice of one or several theories to be implemented in a social-ecological model such as the degree of formalization, degree of completeness, the representation of dynamics. One can see, for instance, that only habitual theory explicitly includes details on the change of decision-making process over time (dynamics). Other theories can be used in dynamic models, but each timestep they will consider the decision problem in the same way, given the information available. Most theories except for the rational and the boundedly rational actor have so far not been used much in formal models, which is not surprising given the breath of decision problems it can be applied to and its relative degree of formalization.

When choosing a theory for implementation in a formal model it is important that the selected theory represents those aspects of human decision-making in appropriate detail that are considered crucial for the particular context or research focus of the model. If, for instance, for a given context, cooperation between users of a natural resource is critical, then theories focusing on interactions with others will automatically be relevant for the modeller. A choice may also be influenced by the degree of formalization of a theory, since a theory that is already highly formalized will be easier to implement into a model, and fewer assumptions on missing elements will have to be made. Finally the degree of completeness of a theory can also be important since a theory that already covers many aspects means that modellers do have to make fewer assumptions than for theories that focus on single elements and leave out others. Note, however, that the degree of completeness relevant for a specific model depends on the research question the model addresses, so in some cases, a very specific theory may be the most adequate. The framework can help identify which aspects a theory focusses on (Table 4) and which details it includes and thus support the choice of a theory to be used in a model. Often, however, it may be difficult to decide which theory will be the most appropriate for the topic of interest. We therefore argue that it is important to include different theories into the model to assess the sensitivity of the results to different assumption about human decision making.

When operationalizing a theory for use in a social-ecological model, one has to make choices on causal mechanisms. In the case of the theory of planned behaviour, for instance, one has to decide how the behavioural, normative and control beliefs are aggregated to determine intentions and how an intention leads to behaviour. Even a well-formulated theory of rational choice will require making choices on temporal and spatial scale of the knowledge available to the agents. For example, will agents take into account the long term consequences of their decisions? And if so, what are their expectations of the decisions of other agents? These choices are necessarily more or less well-founded assumptions that will vary between different model implementations. The framework can thus be very valuable in encouraging modellers to make these assumptions explicit and their effects comparable between different models. It also stimulates a critical reflection on whether the degree to which one has to make assumptions on causality limits the usefulness of a particular theory for social-ecological systems modelling. Such a process can thus help identify theories that are most relevant.

Furthermore, the structure of the framework makes modellers aware of the different elements of decision-making that need to be tackled in any kind of implementation in a formal model. By going through the framework in a systematic manner a modeller will have to think about the relevance of each element, even if a theory does not specify it. For instance, a theory may not be explicit about what information an agent can perceive from the biophysical and social environment. For example, the implementation of the rational actor model shows that one needs to specify a feedback from the biophysical environment if the agent makes decisions over time. The ideal model of the theory cannot be implemented (next to that the agent will always be a boundedly rational actor). The mapping will alert the modeller to the fact that she needs to investigate whether this is an important aspect for the particular decision and decision context to be modelled. This process can be complementary to the use of the ODD + D protocol (Müller et al., 2013) in guiding the development of the decision model. ODD + D (Overview, *D*esign Concepts, *D*etails + *D*ecision Making) is a standard and increasingly widely used protocol for describing ABMs that includes a description of human decision-making. The framework however goes beyond ODD + D in that it structures the decision- making process in more detail into specific elements and specifies how they interact. This enables a more systematic and comparable development of a decision- making model.

5.4. Final Remarks

There is an increasing recognition of the importance of including a broader understanding of human behaviour into the study of social-ecological systems. The inclusion of this knowledge in formal models presents major challenges. The challenge is partly because of the diversity of choice of behavioural theories available for the task of translating human behaviours into formal models, and partly because any chosen theory will unlikely completely specify all aspects of human decision making, hence likely requiring additional assumptions. Our proposed framework is a modest step to facilitate this translation process. The next step for this research endeavour will be the systematic implementation of a set of behavioural theories in models of social-ecological systems. This is particularly relevant in the context of real world resource management problems in social-ecological systems where the implications for policymaking of the complexity and diversity of human behaviour are little known. Applying a set of different decision models can help assess the robustness of a policy to behavioural uncertainty, or explain a particular policy outcome. In this case one would vary the behavioural assumptions while keeping the policy constant. In other cases where the aim is to build theory about features of policies or institutions that lead to certain outcomes maintaining one particular set of behavioural assumptions may be valuable in order to assess the implications of variations in institutional features and allow for the accumulation of knowledge across studies (Diermeier and Krehbiel, 2003).

Implementing different behavioural theories into a formal model allows for a sensitivity analysis of human behaviour within a natural resource management context. We see the value of this sensitivity analysis initially as a conceptual understanding of how different behavioural theories affect the dynamics of social-ecological systems. Moreover, including different behavioural theories on decision-making in formal models of social-ecological systems enables the ability to assess the consequences of a mismatch in behavioural theories for designing policies. For example, one may optimize a tax policy to meet some environmental management goals assuming rational choice of selfish actors. Implementing alternative behavioural theories, we can test the consequences of this policy if actors are not rational and selfish, but make decisions according to other behavioural theories. Such an analysis enables assessing the robustness of the performance of policy options to different assumptions of human behaviour.

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