

Article

A Serious Board Game to Analyze Socio-Ecological Dynamics towards Collaboration in Agriculture [†]

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Abstract: Climate change exacerbates water scarcity and associated conflicts over water resources. To address said conflicts and achieve sustainable use of water resources in agriculture, further development of socio-ecological adaptations are required. In this study, we evaluate the ability of MAHIZ, a serious board game, to analyze socio-hydrological dynamics related to irrigated agriculture. Gameplay involves the player's decision-making with associated impacts on water resources and crop productivity in diverse climate and policy scenarios. We evaluated MAHIZ as (1) an innovative science communication and sustainability education approach, and (2) a data collection method to inform socio-hydrological theory and models. Analysis of 35 recorded game sessions demonstrated that MAHIZ is an effective education tool about the tragedy of commons in agrohydrology and was able to identify important decision-making processes and associations between critical social parameters (e.g., communication, trust, competence) and the evolution of collective action. MAHIZ has an open game design, so the approach can be adapted for both scientific insight and outreach.

Keywords: socio-hydrology; irrigation; serious games; decision-making parameters; agent-based modeling

1. Introduction

Agriculture is the largest global water user and significantly impacts the hydrological cycle, including the intensification of drought and flood events [1]. Future increases in agricultural water demand are predicted to occur alongside increases in conflicts over water resources [2]. To reduce negative social and environmental impacts, social adaptations are needed [3]. Agrohydrology as a discipline has historically focused on interactions between hydrological, biological, and agronomic processes [4], but effective sustainable adaptation requires a full understanding of the drivers behind the stakeholders' decisions and impacts [5]. Furthermore, the gap between knowledge and policy implementation is due to the main challenges (Figure 1) which mainly involve the participation from stakeholders, policymakers, professionals, and society to analyze and communicate an inclusive sustainable vision.

The novel scientific field of socio-hydrology, which seeks to understand the co-evolving feedback between social and hydrological systems [6], is one promising attempt to couple socio-ecological outcomes. Typically, socio-hydrology approaches consist of coupled human-water models where stakeholders are modeled as homogeneous actors [7] or using proxy variables like environmental degradation [8] and community sensitivity [9].

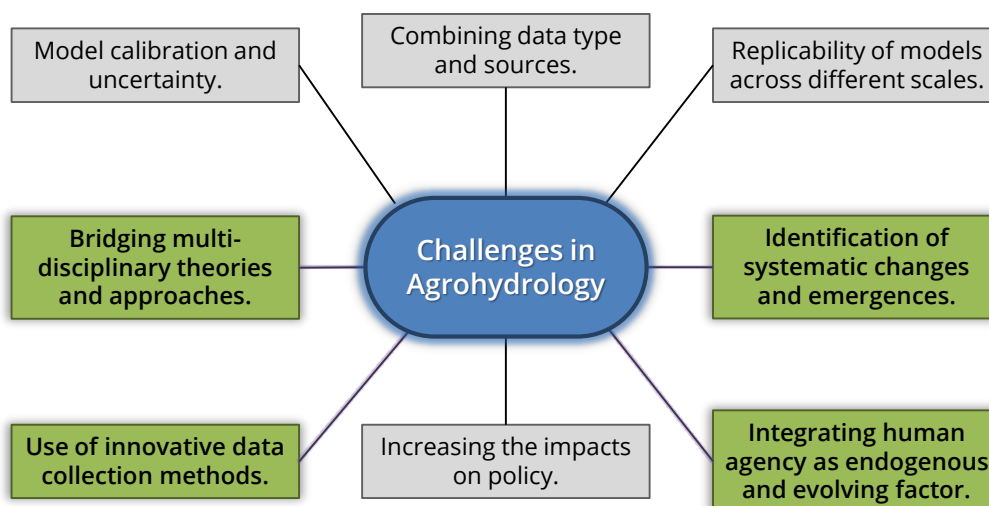


Figure 1. Current challenges in agrohydrology (adapted from Elsayah et al. [10]). Our study focuses on the challenges marked in green.

The use of agent-based models (ABM), which simulate human interaction with ecological systems at the level of individual ‘agents’, in socio-hydrology has increased over the last few years [11]. Kaiser et al. [12] evaluated water-related ABMs and identified eight common types of agents (e.g., agricultural, domestic, industrial, etc.) and highlighted the lack of consistency and inadequate grounding of the decision-making process on these agents [13]. Decision-making representations are usually simplistic concerning the behavioral side related to farming decisions. Recent research (e.g., Schlüter et al. [14], Groeneveld et al. [7], and Huber et al. [15]) found few attempts to model farmers’ emotions, values, learning, and social adaptations, which highlights the need to improve the representation of diversity in decision-making processes in agricultural ABMs. Structural and causal frameworks from social disciplines could be a promising approach to capture the temporal and spatial triggers of the agent’s decision in agrohydrological systems. Evolutionary game theory approaches have been used to estimate optimal agricultural water management strategies (e.g., irrigation or pumping groundwater dilemmas [16]) by considering ecological and economic parameters in the decision-making processes [17]. These dilemmas are based on Hardin’s theory [18], known as “Tragedy of the Commons”, that describes the degradation of shared resources due to over-exploitation [2]. Free-riding is a common driver of over-exploitation while collaboration (i.e., collective action) is considered to be a potential solution [2,19]. Collective action, defined as a group strategy to achieve a common objective [20], is a dynamic social process enabled by parameters such as communication, trust, and competence [21]. Understanding these social parameters and their impacts on the environmental system is critical to identify effective adaptation strategies.

Socio-hydrological models have typically used economic theories, such as rational choice theory [7], which have been proven to be an unrealistic representation of human decision-making in common-pool resources [22]. Furthermore, several other behavior theories have been implemented throughout the years. Schlüter et al. [14] with the MoHuB framework analyzed the most common behavior theories in natural resource management (Table 1). These empirically grounded theories have been used to analyze the critical decision-making parameters towards collective action [23]. However, integrating these theories into process-based biophysical models remains challenging due to a lack of data for model development and parameterization. Heuristics have been used to represent decision-making processes in natural resources management, where the strategic interaction between agents is the main focus [24].

Table 1. Key assumptions of the behavior theories of the MoHuB framework [14].

Theory	Origin	Description
Homo economicus (HE)	Economics	Rational choice theory.
Bounded Rationality (BR)	Economics, Psychology	Rationality is limited by available information and cognitive capacity.
Theory of Planned Behavior (TPB)	Environmental Psychology	Behavior is mediated by attitudes, subjective norms, and control beliefs.
Habitual Learning (HL)	Biology, Psychology	Reinforcement learning of actions based on rewards and/or lack of them.
Descriptive Norm (DN)	Social sciences	Behavior is influenced by the perception of what is socially acceptable.
Prospect Theory (PT)	Psychology	Behavior is influenced by the willingness to seek or avoid risk.

Participatory approaches, such as interviews, workshops, spatial narratives, and games [25], have been used to formalize heuristics by engaging the knowledge of stakeholders in specific stages of the modeling process (e.g., conceptualization, validation, calibration) [26]. Participatory data collection methods have several advantages, including the possibility to record and analyze every decision made by diverse stakeholders such as farmers, policymakers, researchers, students, and teachers using effective mechanisms like role-playing. Role-playing has been very effective as a scenario-based analysis of decision-making processes [27]. Most participatory approaches require a simplification of the real system. For efficient simplification, concepts from game theory have been implemented [28]. For example, Gomes et al. [29] presented a capacity-building game that combines game theory and role-play in a community in Bangladesh. Furthermore, role-playing has been combined with computer models in an approach known as Companion Modeling (ComMod) [30] that has been largely used in various socio-ecological contexts [31]. The ComMod approach consists of three stages [26]:

1. Simplification of the system by gathering the relevant information of the system to include in the model.
2. Validation of the cognitive model by testing the different decision-making processes between the agents with the participation of stakeholders.
3. Analysis of the system dynamics and the interactions between stakeholders. This phase consists of role-playing and computer simulation.

Serious games are one participatory approach that has been used to elicit social values, understand stakeholder responses to diverse environmental scenarios, and to teach about the implications of their adaptations [32]. The current definition [33] of serious games was introduced in 1970 as "... games [that] have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement." (Abt 1970 p.9 [34]). Water-related serious games have been found to facilitate the understanding of the complexity of the real world, foster multi-stakeholder collaboration, and enable social learning [35]. While there are examples of serious computer games related to irrigation (e.g., Irrigania by Seibert and Vis [36]), relatively less research has been done on serious board games for water management. Serious games have been implemented as education for sustainability (Efs) approaches to teach and bring together diverse types of stakeholders to open channels of communication and provide new solutions towards sustainability [32,37].

Study Objectives

Our overarching hypothesis is that serious board games can be used within participatory modeling approaches to help address the current challenges in agrohydrology. While advances in socio-hydrological models have been made, there are still limitations of data availability and of extrapolation of the decision-making process to make predictions and impact policymaking. The scope

of this study is limited to the six behavior theories from the MoHuB framework (Table 1) and three critical decision-making parameters, which are:

- **Communication:** the interchange between players of thoughts, opinions, or information by speech.
- **Trust:** the confidence of a player on the integrity and ability of another player(s) or action.
- **Competence:** player’s self-confidence of having suitable skills, knowledge, and/or experience to win the game.

This study focused on the development and evaluation of a serious board game to analyze socio-ecological dynamics towards collaboration in agriculture. The main objective of the study was to evaluate the serious board game, MAHIZ, for two purposes: (1) as an innovative and enjoyable EfS approach for the general public and (2) as a data collection method for decision-making processes which can inform socio-hydrological models such as ABMs. To accomplish this, the specific objectives of the study were to:

- Develop a serious game to teach about the tragedy of commons in water resources and foster social learning;
- Identify the presence of diverse behavior theories among MAHIZ players;
- Evaluate the different decision-making processes and critical parameters related to agrohydrological irrigation;
- Improve skills and knowledge within the hydrology scientific community to support cross-disciplinary collaboration to integrate decision-making processes into socio-hydrological simulations.

2. Methodology

2.1. Description of MAHIZ

MAHIZ is a euro-style board game (i.e., strategic game that focuses on individual development and resource management [38]) for up to 4 players, designed following the ComMod stages [26] and the Triadic Game Design (TGD) approach [39] (see Figure 2). The use of the TGD was to make sure that the balance between reality, play, and meaning of the game was accomplished and to ensure the serious game purpose.

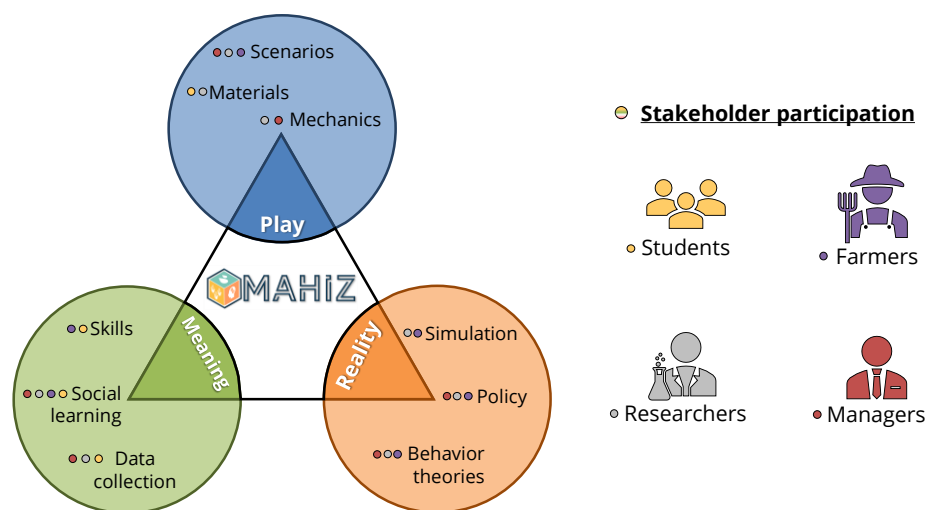


Figure 2. Adapted Triadic Game Design.

The term “maize” (also known as corn) is derived from the ancient word *mahiz* from the Taino language. This was used as an inspiration for the name of the game and to represent the only

crop present in the game. The board game components (i.e., boards, pieces, and cards) are shown in Figure 3a. The game represents a simplified representation of the tragedy of commons in agrohydrology (see Figure 3b) that enhances player engagement and social learning. We organized play-testing sessions with farmers and board game developers to ensure the effectiveness of this representation (see Supplementary Materials Part (B)).

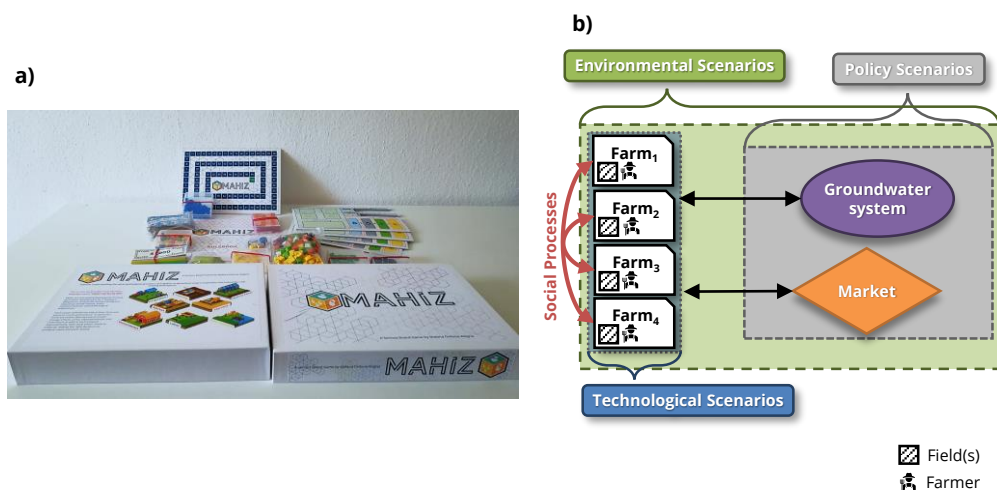


Figure 3. MAHIZ: (a) Board game components and (b) Agrohydrological system considered.

Gameplay

At the start of the game, players have a small field, initial budget, and basic conditions to grow maize. The gameplay is a sequential process defined by several scenarios. These scenarios consist of varying policy and weather conditions, availability of resources, and market price. The implementation of diverse technologies offers players abundant possibilities to optimize their farm production. The available technologies are:

- **Irrigation technologies** that allow the player to take water from the communal well where the order of the players represents the distance to the well.
- **Hybrid seed technologies** that allow the player to use specialized seeds with limited transpiration to adapt to the changes in the system.

The technologies available have costs that include electricity, materials, fertilizer, etc. The costs and revenues of the implementation of technologies and land reflect the financial considerations and behavior of farmers in reality. Each round in the game consists of the following three phases:

1. Discussion and initial decision of the implementation of technologies and farmland expansion;
2. Weather forecast by rolling dice and decision of the level of technology;
3. Harvest where players assess the productivity of their farm practices.

Every fourth round there is a market phase where players sell their yield. Ultimately, the winner is the farmer who has established the best farm practices with the most maize produced and profit earned throughout the game. The full description of the board game mechanics can be found in the rule book in Supplementary Materials Part (A).

MAHIZ simulates farmer's decision-making and the impact upon the groundwater commons and crop yield in diverse climate and policy scenarios. The optimal strategy for a player in MAHIZ can be either collective action towards long-term sustainable agricultural water management or free-riding towards short-term economic gain. The simplifications of the real system used in the board game were taken from game theory approaches (i.e., irrigation and pumping water dilemmas). These consisted of

the restriction to grow only maize, only two choices of technologies (i.e., irrigation and hybrid seeds) and the change of location from the well at each turn (i.e., iteration of upstream and downstream players). The climate and policy scenarios (see Table 2) simulated in the game were selected from a variety of real agrohydrological systems.

Table 2. Description of MAHIZ's scenarios.

Type	Scenario	Definition in the Game
Climate	Drought	The rain is reduced.
	Hot and Early Spring	The evapotranspiration is increased.
	Flash Flood	The yield is reduced based on the flood intensity.
	Cold and Late Winter	The yield is reduced.
Policy	Groundwater	The operational costs of irrigation technologies are increased, and rainfed agriculture is subsidized.
	Environmental	The operational cost of the technologies is increased.
	Technological Advance	New irrigation technology upgrade is available for investment.
	Organic Demand	The operational costs of hybrid seed technologies are increased, and organic farming is subsidized.
	Biological Advance	New hybrid seed technology upgrade is available for investment.
	Deficit Irrigation	New deficit irrigation technologies are available for investment.
Economic Market	The market price is negotiated between players.	

2.2. Game Sessions

From April to December 2019, 35 game sessions (see Supplementary Materials Part (B)) were organized. We aimed to gather players with a broad range of expertise of the real agrohydrological system and academic backgrounds, from stakeholders (i.e., farmers and managers), observers (i.e., researchers, students, and model developers), and board game developers and aficionados. These diverse groups were involved to include diverse insights:

- Playing with **hydrological researchers and model developers**: the aim of the experiments was to identify the need for human agency and to introduce different behavior theories for hydrological models.
- Playing with **farmers**: the aim was to validate the dynamics represented by the game and to establish negotiations methods towards collaboration.
- Playing with **the general public**: the aim was to teach about the tragedy of commons in agrohydrology in a fun and simple way.

In our 35 sessions, players were mostly from academia (students and senior researchers) from disciplines related to water research. Smallholder farmers were the second biggest participant group, whilst the remaining participants consisted of the general public with board gaming experience. Each game session consisted of a limited number of participants (up to 4 per game) and rounds played (i.e., 12) with a specific order of appearance and iteration of the climate and policy events. Additionally, we developed a dedicated computer interface for data collection. For consistency in the experiments, the initial groundwater level and resource availability for each player were modified based on the number of players in each session to enhance the identification of free-riding or collective action behavior by players and moderators. Each game session consisted of:

1. A careful description of the basic concepts relating to the tragedy of commons whilst trying to minimize confirmation bias
2. An adapted game of MAHIZ

3. A debriefing with the written feedback form.

The recorded game sessions took place mostly throughout Germany but also in the Czech Republic, Austria, France, Mexico, and the United States. A total of 113 players were recorded, where each player is the source of the data points or observations that were analyzed. All players participated voluntarily by responding to an open invitation and each player signed a consent form to participate in the study. The game sessions were facilitated by a moderator team comprised of the authors and two assistants who oversaw the data collection and keeping track of the interactions between players.

2.3. Data Collection Methods

There were two primary data collection approaches:

- **In-game observations:** consisted of the use of the dedicated computer interface to capture the decisions made by players during MAHIZ. The recorded decisions included the evolution of groundwater resources, technology implemented, yield, and climate variability.
- **Debriefing:** consisted of written feedback form (see Supplementary Materials Part (C)) and facilitator-guided conversation to assess the game and self-assess player learning. This feedback enabled the validation of the simplified representation of the agrohydrological system in four specific ways: (1) The players' first thoughts and emotions of the game. (2) An analysis of decision-making processes experienced in the game and representations of the diverse processes in theoretical models. (3) Players were asked to analyze the behavior theories presented in the MoHuB framework and rank these theories based on how representative of their strategy (i.e., decision-making process) used in the game. (4) A discussion of critical decision-making parameters (i.e., communication, competence, and trust) regarding collective action and free-riding behavior in agrohydrology.

Table 3. Data structure of in-game observations from recorded game sessions.

Variable	Description
<i>Game session</i>	Date (dd.mm.yy).
<i>Round number</i>	1...12.
<i>Scenarios</i>	Climate and policy scenarios of each round. The same sequence was used for every game session.
<i>Identifier</i>	Observation number 1...113.
<i>Color</i>	Chosen color by players. No other personal data from participants was collected.
<i>Rain dice results</i>	(1...6). Weather forecast.
<i>Sun dice results</i>	(1...6). Harvest factor.
<i>Technology implemented</i>	Irrigation/Hybrid seeds/None/Both.
<i>Level—Irrigation</i>	Number of drops taken from the communal well by each player.
<i>Level—Hybrid seeds</i>	0...3.
<i>Maize produced</i>	Number of maize pieces produced.
<i>Profit</i>	Money earned based on maize pieces sold and negotiations between players.
<i>Communication</i>	Active/Passive
<i>Trust</i>	Open/Closed
<i>Competence</i>	Satisfied/Dissatisfied

We tracked critical social decision-making parameters (communication, trust, competence) as categorical variables by recording the comments and questions made by the players. We considered active participation to be the occurrence of in-depth discussions, whereas relative passive participation to be characterized by little communication or no communication between the players. Trust was evaluated by identifying the negotiations made by players from the recorded comments and analyzing

the continuation or interruption of said negotiations. Competence was evaluated by the satisfaction based on the players' comments and actions before the weather forecast (i.e., if the player decides the amount of water to extract without knowing the condition of the round).

The structure of the data collected by the in-game observations is presented in Table 3 and by the feedback in Table 4. Effectiveness of MAHIZ and the presented approach as an EfS approach was evaluated by asking the players to judge the game according to the length, theme, game strategy, balance of mechanics, ease, and entertainment. To evaluate the effectiveness of MAHIZ as a data collection method for socio-hydrological research, our analysis focused on identifying important decision-making parameters and processes (i.e., heuristics) and exploring the diversity of behavior theories and their impacts on the human-water system. The decision-making processes were identified by analyzing the player decisions regarding technology and level implemented in every round.

Table 4. Data structure of the player feedback from recorded game sessions.

Variable	Description
<i>Comments and Observations</i>	Count of comments or conversations made by each player and the type of each comment (e.g., pro-collaboration, negotiation strategies, defiance of trust, selfishness).
<i>Feedback</i>	Opinion about the gameplay and structure of game sessions.
<i>New Knowledge</i>	Yes/No.
<i>Behavior</i>	Static or dynamic decision-making processes experienced throughout the game.
<i>Ranking of behavior theories</i>	Ordered from 1 to 6 based on the similitude between the theoretical description and the strategy implemented in the game.

2.4. Analysis Methods

To evaluate the relationship between the decision-making parameters and the behavior theories, an asymmetric association analysis was carried out using the Goodman Kruskal R package [40]. This package estimates how closely two pairs of data points are associated and the strength of said associations. Goodman and Kruskal's tau (τ) measure is asymmetric, meaning the association between variables x and y are not the same as that between y and x [41]. Hence, it quantifies the two-way relationship between categorical variables that are continuous or discrete [42]. We set a τ threshold of 0.6 to represent a strong association.

While uncertainty is inevitable in social science data collection, we attempted to minimize uncertainty via the development of the dedicated computer interface to collect data and training the moderator team on the rules of the game, the identification of the critical decision-making parameters, and the MoHuB behavior theories. During each game session, epistemic uncertainty was reduced by ensuring that players had an appropriate level of understanding of the system and definitions of the main concepts of the game. Furthermore, strategic uncertainty was handled by opening all channels of communication during and after the game sessions. The reproducibility (i.e., measurement uncertainty) was tested before the recording game sessions. Changes were made in the game contents to ensure the players with no background knowledge of the system were able to fully understand it and the variables of the data collection were organized in a strict structure.

3. Results

3.1. Evaluation of MAHIZ as an Education for Sustainability Approach

Figure 4 shows the players' feedback on MAHIZ. Participants found the game easy to understand and play with multiple opportunities to win. According to more than 90% of the players, the board game created a fun setting to openly discussed and analyze a broad range of topics. Players were able to find real-life applications to the game outcomes. In particular, the players with less familiarity with socio-hydrology enjoyed MAHIZ as an introduction to social issues within hydro-sciences.

The length of the game sessions was generally acceptable, however in a few game sessions due to open communication, the discussions were considered to take too long.

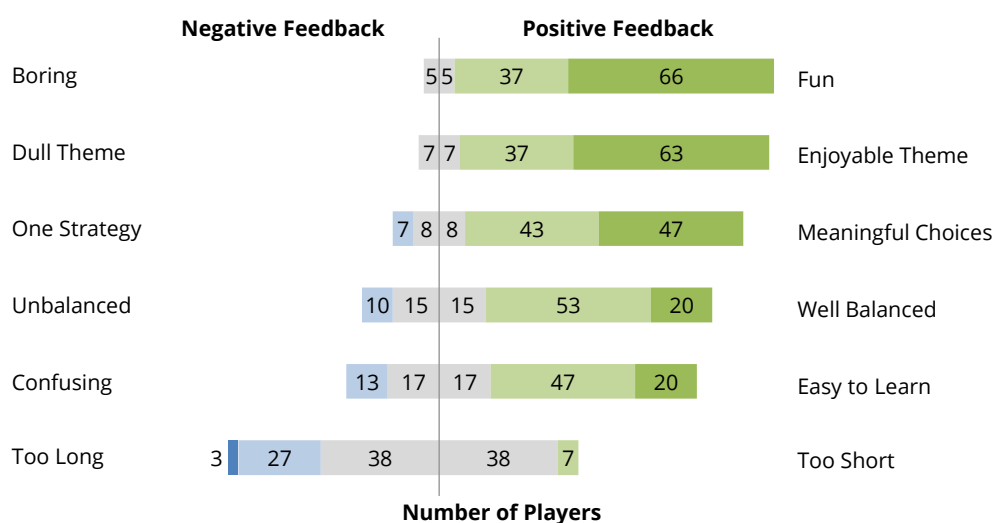


Figure 4. Feedback of MAHIZ game sessions. The values in green indicate the positive feedback, values in grey indicate neutral feedback, and values in blue indicate the negative feedback.

The game sessions allowed knowledge building through experiencing and discussion of conflicting social, economic, and environmental values in a theoretical agrohydrological scenario. More than 70% of the players confirmed to have obtained new knowledge by playing MAHIZ, 21% answered “maybe” and 9% answered “no”. We found that even players with knowledge in agrohydrological issues generated new knowledge during the game session. Learning in MAHIZ was described by the players in the feedback form in the following way:

“The idea of the game is really nice and realistic. The game represent almost all the issues related to the complexity agriculture and irrigation and allows everybody to learn at their our time.”—Bounded Rationality Player [25.04.19]

“It was a very good experience and well developed game. I learned about the social and economic aspects of being a farmer. I like the translation of these issues into a board game.”—Theory of Planned Behavior Player [11.07.19]

“I liked the whole idea. There was nothing to be disliked. I learned the importance of team efforts in sustainability. The game is exciting and attractive for the slow learners or people with little knowledge of hydrology.”—Descriptive Norm Player [30.07.19]

“I look at the agriculture from another perspective. I learned that sustainability in agriculture involves many factors, more than climate change and to ask for farmer to be sustainable could mean bankruptcy.”—Prospect Theory Player [06.08.19]

“I like the game a lot, it’s fun and it needs a mid-term strategy which is exciting and keeps the player focused on the game and learning throughout the entire session.”—Theory of Planned Behavior Player [25.09.19]

“I liked the options to advanced the technologies, this help to realize the effects on draining the water supply. I also liked that cooperation is always an option and not mandatory, this allow us to learn how to build connections and the direct impact on the environment.”—Bounded Rationality Player [27.10.19]

“I like the idea about a board game to simulate the decision making process in agriculture. The more you learned about working together but also being selfish, the more opportunities you have to win.”—Homo Economicus Player [21.11.19]

Based on the self-assessments in feedback forms and debriefing conversations, we can conclude that players increased their knowledge of agricultural water resources management, resiliency of social and environmental systems, and impacts of variable climate conditions on optimal water management. More importantly, players viewed serious games as a promising approach to educate and learn about socio-ecological decision-making. Students and researchers suggested multiple other environmental challenges that could be addressed through a serious game (e.g., water quality in rivers, blue/green cities, trans-boundary issues, etc.).

3.2. Identification of Behavior Theories

Among the behavior theories analyzed (Figure 5), Theory of Planned Behavior and Bounded Rationality were identified as most representative by 29% ($n = 33$) and 22% ($n = 25$) of the players respectively, and Homo Economicus and Prospect Theory were identified as least representative by 54% ($n = 60$) of players. However, many players pointed out the limitations of selecting just one theory as most representative. According to 70% of the players, their strategy could be represented by multiple behavior theories throughout the game, most commonly changing from Theory of Planned Behavior and Homo Economicus to Bounded Rationality and Habitual Learning. This dynamic behavior indicates that ascribing static behavioral properties in socio-hydrological models may be flawed. In the debriefing phase, players suggested how to represent dynamic changes in behavior theory within socio-hydrological models such as ABMs, including behavioral rules based on diverse theories and parameters like social network, satisfaction, and trend of climate variations. Furthermore, players suggested that current environmental policies could trigger free-riding behavior.

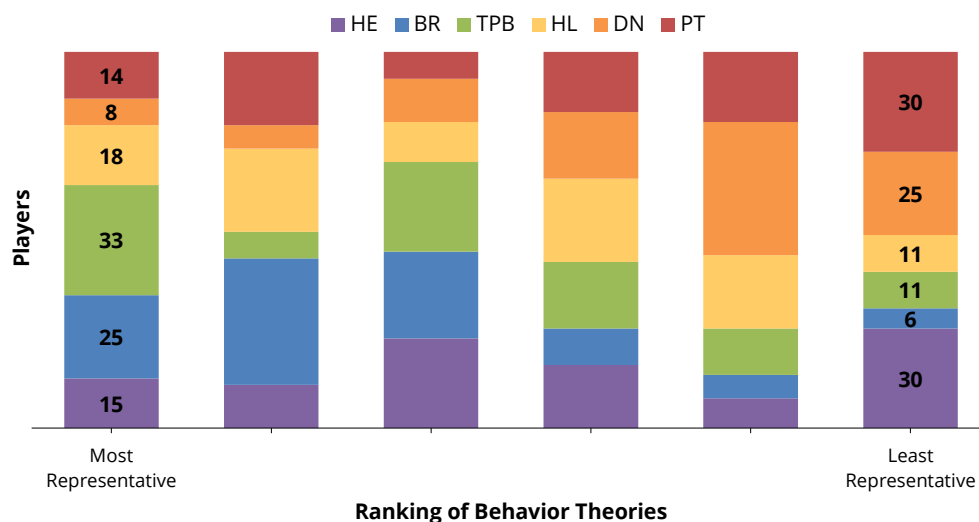


Figure 5. Ranking of behavior theories based on the representation of players' decision-making in the game sessions.

The overall analysis of social parameters and behavior theories indicates that active communication and trust can lead to collective action which mostly happened in Theory of Planned Behavior and Bounded Rationality players, but too much communication and/or competence can lead to free-riding which mostly happened in Homo Economicus and Descriptive Norm players. Prospect Theory players showed both collective action and free-riding behavior.

3.3. Analysis of Decision-Making

We identified four main heuristics used by participants in MAHIZ:

1. **Imitation:** a player copies a strategy of another player due to misunderstanding of the system dynamics or to the low efficiency of their previous strategy;
2. **Comparison:** a player selects a strategy based on a comparison of productivity and economic resources with another player. Reassessment of strategy occurred very often and was triggered by the climate and policy events in the game.
3. **Deliberation:** a player decides based on a selfish simplified optimization of the conditions of the round. It mostly happened during the first round due to the player's limited knowledge of the system dynamics and when a player decided to use no technologies because of the lack of economic resources.
4. **Repetition:** when a player considered to have found the optimal strategy then the player continues with the same decisions regarding the implementation of preferred technology and level.

In most game sessions, the optimal winning strategy involved the strategic implementation of these decision-making processes and the understanding of the underlying system dynamics. The analysis of critical decision-making parameters (i.e., communication, competence, and trust) focused on the relationship between these parameters and the evolution of collective action or free-riding behavior. Most winning players exhibited both collective action as upstream players and free-riding behavior as downstream players.

Communication: In 80% of the game sessions, little communication between players was observed in the first round. Communication gradually increased after the first market phase, where players experienced different economic conditions. The liveliest discussions about collective action occurred during the game rounds where policy and climate events concurred with bad results in the dice. These discussions explored many aspects, including reflections on how real-life communication constraints could be overcome and how improved models and policies could help to achieve sustainable irrigated agriculture.

Trust: Power dynamics were observed between upstream (first player) and downstream (last player) players in each round. Downstream players often started the negotiation process where trust was a critical parameter. Relatedness (i.e., pre-existing friendship between players) increased the influence on each other's decisions by enhancing trust-building. A strong connection among players was correlated to frequent and in-depth communication and collective behavior. In the game sessions where free-riding was observed, players seem to build trust with other players to punish the free-rider. The results indicate that trust and incremental benefits lead players to collaborate when the appropriate policy was in place.

Competence: When the players' competence was high, players cared more about their economic conditions and prefer to overuse resources. When the player's competence was low, players cared about the environmental conditions and other player's economic conditions, leading to protection or restoration of resources and diverse negotiation skills. Environmental and economic degradation was positively correlated to the player's competence. In some game sessions, a single highly-competent player tended to take a leadership role, while in other cases the players followed a more collective decision-making process. In games with collaborative leadership, there was a stronger tendency towards balanced resource distribution among all players.

As a result of the analysis of the critical decision-making parameters, a complex relationship between the critical parameters and collective action was observed. Figure 6 shows a graphical summary of the results obtained using the Goodman Kruskal R package, i.e., 9×9 array with the categorical variables (6 behavior theories and 3 social parameters). The asymmetry found between variables is present mostly between behavior theories and social parameters. The association between the social parameters (communication, trust, and competence) and the Theory of Planned Behavior

(TPB) is $\tau(x, y) = 0.26, 0.4, 0.55$ respectively and the opposite association $\tau(y, x) = 0.68, 0.7, 0.71$ respectively. This result means that social parameters are predictable from the choice of Theory of Planned Behavior as an optimal strategy but said choice gives little information about the level of communication, trust, and competence between players. More generally, the plot shows weak τ values between behavior theories and thus gives no information regarding the variability of theories in the game. Important associations were estimated between the social parameters and between said parameters and the behavior theories. Communication show a strong symmetrical association with trust with $\tau > 0.85$. Competence was strongly associated with Homo Economicus (HE), Bounded Rationality (BR) ($\tau > 0.7$), and Prospect Theory (PT) ($\tau = 0.63$).

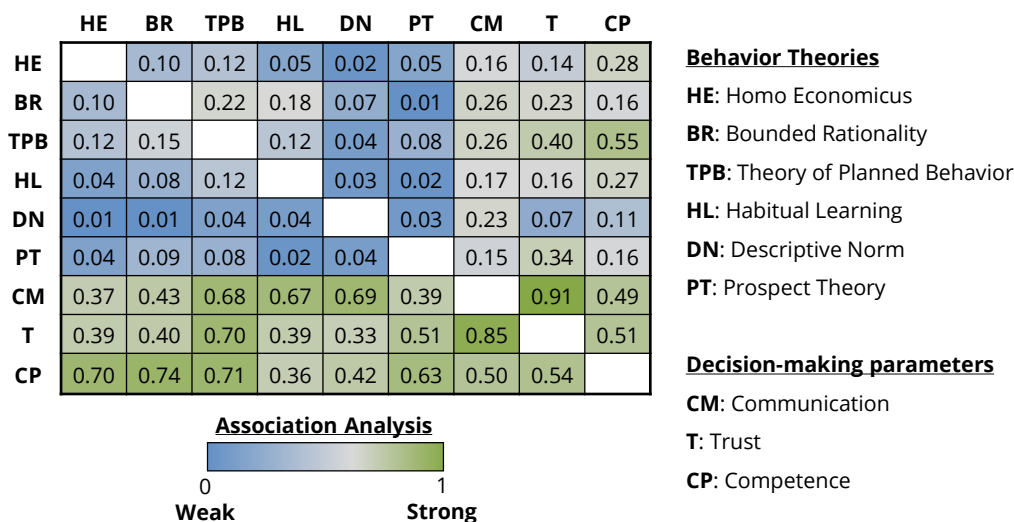


Figure 6. Analysis of asymmetric association (Goodman and Kruskal’s τ) between behavior theories and decision-making parameters. The colored numbers show the numeric and graphical representations of the Goodman-Kruskal $\tau(x, y)$ estimations from the x (row) to y (column).

3.4. Analysis of Socio-Hydrological Dynamics

The theoretical agrohydrological scenario simulated in MAHIZ consisted of a trade-off analysis of groundwater extraction vs economic yield. During the game, this is analyzed by the number of drops each player takes from the well for irrigation and the number of maize pieces they produced based on their farming strategy (i.e., technology implementation and negotiation with other players) and the climate variability based on dice. We found that there was a range of possible yield outcomes for a given level of groundwater availability, and vice versa (Figure 7a). Different behavioral theories led to different optimal strategies, highlighting the strengths and limitations of each behavior to represent the variability of complex decision-making dynamics. The ideal solution of the water productivity trade-off showed in Figure 7a as the top right region, maximizes yield while minimizing the amount of groundwater extracted. On average, the Theory of Planned Behavior players showed the highest groundwater savings (8.39 ± 3.07 drops per turn used on average) with sustainable yield (7.56 ± 2.75 maize pieces) while Habitual Learning players (4.59 ± 2.98 drops per player) and Homo Economicus players (5.57 ± 2.52 drops) showed higher over-exploitation of the groundwater but contrasting yield outcomes. Homo Economicus players showed the highest yield (9.60 ± 2.48 maize pieces per turn) while Habitual Learning (4.89 ± 2.38 pieces per player) and Descriptive Norm players (4.01 ± 2.27 pieces per player) showed the lowest yield.

The most efficient strategies (i.e., Pareto front) found by the diverse theories are shown in Figure 7b. All the efficient strategies for the Theory of Planned Behavior players are within the ideal solution region, while Homo Economicus and Bounded Rationality players showed efficient strategies with lower yields and Prospect Theory players with higher groundwater extraction. The highly variable outcomes by Habitual Learning and Descriptive Norm players result from the complex social process.

Few cases of free-riding players were identified, mostly by Homo Economicus and Prospect Theory players. Free-riding players tended to look only one or two turns into the future and ignored the long-term effect of their over-exploitation of the groundwater. In the game sessions where free-riding occurred, in-game conversations indicate that all players were aware of the selfish behavior, and players resorted to collaboration against the free-riding player.

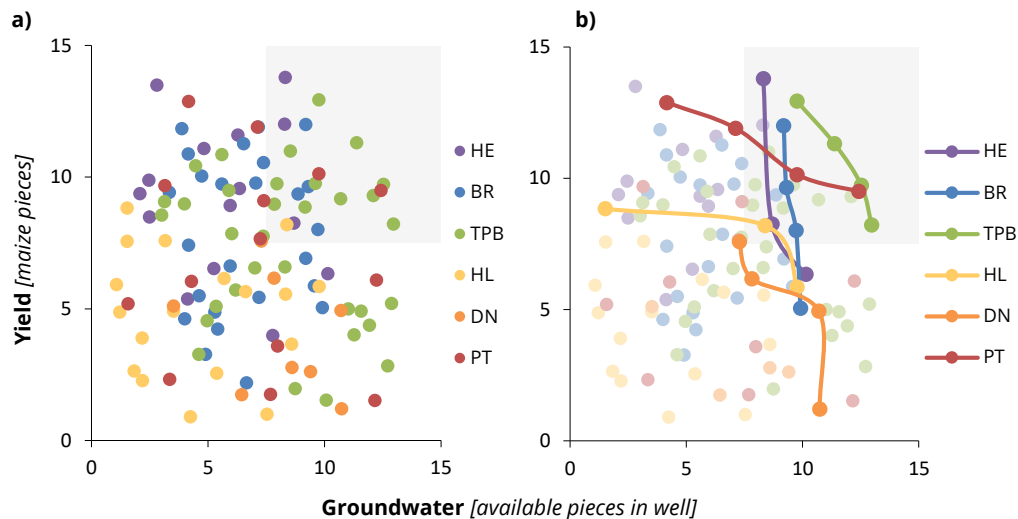


Figure 7. (a) Trade-off between yield and groundwater extraction categorized by diverse behavior theories. (b) Pareto optimal solutions by behavior theory.

The use of irrigation technologies showed a complex relationship to groundwater availability. In cases of low groundwater levels, players tended to use one of two strategies: (1) continue to extract groundwater leading to large reductions in yield and the future use of the irrigation technologies; or (2) negotiation between players to share the resources and to implement alternative technologies. Climate variability had a significant effect on the decisions by the upstream player (i.e., first player in each round) regarding investment and groundwater extraction. The mutual exchange and trust between the upstream and downstream players was one of the most important variables in the effectiveness of collective action. Social isolation led to an overuse of the resources and a bigger inequality in agricultural production. Additionally, we qualitatively observed that players who constantly irrigated in early rounds do not have the same perception regarding the climatic variability compared to other players. Players who mostly used irrigation relied on groundwater availability rather than on the result of the rain dice.

4. Discussion

Environmental resources, such as groundwater are “vital commons” due to their importance to the availability and supply of other resources [43]. A better understanding of human-water interactions is needed to find the best adaptation strategies to promote agricultural production while protecting water resources. The main goal of our study was to evaluate the ability of a serious board game to capture diverse decision-making processes and to teach about the two-way feedback between human-water systems.

4.1. MAHIZ—An Education for Sustainability Approach and Data Collection Approach

MAHIZ facilitated the player’s understanding of complex agrohydrological issues and the analysis of the dynamics between social and hydrological systems. This is the first proof of concept of an approach that combines the ComMod stages with serious game design. While several qualities of serious games to improve learning and cognitive development have been identified, evaluation of the efficacy based on pedagogy is still missing. Our evaluation of MAHIZ is facilitated by implementing

the Triadic Game Design approach. Our findings are similar to the issue-situation-based board game *Water ark* [44], where players learned about water resources issues and moved from self-interest strategies (i.e., free-riding) to altruistic collaborative strategies (collective action). While our results indicated a high level of player engagement and knowledge generation, this was with a relatively limited sample size primarily sourced from academia. To evaluate the potential for MAHIZ and other serious board games to the wider public, further testing of the approach is needed with more data, scenarios, and audiences.

The debriefings were facilitator-guided conversations with the goal of leading the players to self-assessment of their learning during gameplay [45]. Research suggests that debriefings should revolve around the four E's: events, emotions, empathy, and explanations [46]. During some debriefings, facilitators struggled to go through the four E's because the players were tired and had limited interest in analyzing their decisions.

Our results show the potential of MAHIZ as a data collection method because it facilitates the adaptation of rules and scenarios for specific audiences and/or experimental designs. Games designed for decision analysis need to be easily adaptable and should not support a specific strategy but to let a neutral feedback loop emerge from the game mechanics [47]. MAHIZ identified effectively multiple relationships between social parameters (e.g., communication, competence, trust) and behavioral theories as well as dynamic changes between the representation of behavior. Since this study was designed as a proof-of-concept, we focused our analysis on identifying diverse behavior theories within a broad theoretical agrohydrological scenario. Further development and testing must be done to test the validity of each theory and the associated decision-making parameter. MAHIZ's unique open board game design facilitates this. Past role-playing computer and classroom games developed using the ComMod approach for decision-making analysis have typically required previous knowledge and specialized software [31,48–50]. With MAHIZ's relatively simple board game format, it is possible to adapt to multiple different scenarios, such as region-specific and/or audience-specific considerations.

4.2. Decision-Making Processes in MAHIZ

Our results indicate that MAHIZ effectively captured socio-ecological behavior observed in previous studies. Social experiments by Le Page et al. [31] and Bousquet et al. [26] identify communication as a critical parameter for optimal common-pool resources management strategies, which is supported by our association between communication and behavior theories. Further, the willingness of players to suffer to get rid of free-riders and increase collective action with other players is supported by previous research [36,49]. Our analysis found that behavior has a dynamic nature as players switched their choice between the behavior theories from the MoHuB framework, and additional work is needed to quantify the triggers for these switches and represent these dynamics in models. This indicates that serious board games have potential to meet key socio-hydrologic research needs, in particular to (i) analyze the evolution of collective action as an emergent process, (ii) carry out a sensitivity analysis of the impact of these behavior theories on the system dynamics, and (iii) assess the impact of different behavior theories on policy-making [51,52]. We found strong and contrasting relationships between the critical social parameters of trust, communication, and competence and each of the behavioral theories. In general, high levels of competence in the absence of communication and trust tended to increase the prevalence of free-riding (Figure 5). This agrees with previous work by Speelman et al. [53] that showed leadership, relatedness, and communication develop collaborative decision-making and by Foster et al. [54] that showed a complex nonlinear relationship between irrigation behavior and groundwater availability. The effect of communication has been studied before (e.g., Le Page et al. [31], Seibert and Vis [36], and Baggio et al. [55]), wherein most experiments, communication at the beginning was observed to be very intense consisting of strategy planning. In this approach, communication and cooperation are encouraged from the beginning but most of the players' communications in the first round were mostly to the moderator and not between the players. The approach allows for an analysis of the origins and evolution of the collaboration. Other studies

(e.g., Malawska, and Topping [56]) have shown that robust implementation of different behavior theories does not improve agricultural ABM performance, so developing best-practices for integrating different behavior theories and/or realistic representation of decision-making into ABMs and other socio-hydrologic models remains a research priority.

4.3. Limitations of the Presented Approach

While the results presented above demonstrate that MAHIZ has potential for informing socio-hydrological research, the game's efficacy may be improved by addressing several limitations in future work:

- *Number of players:* MAHIZ was designed as a euro-style board game with strategic interactions. To be able to analyze these interactions a restriction of players is necessary. However, we produced two full prototypes of the game, hence the game sessions were restricted to a maximum of eight players. The initial conditions of the game were adapted so that the number of players had a minimum impact on the evolution of cooperation within players. Players in the game sessions with only two players showed higher resistance to change attitudes from direct persuasion by the game mechanics.
- *Length of game sessions:* The games plus debriefing proved to be too demanding in a few game sessions with four players. In contrast, in some short game sessions, the player's response was not fast enough to reflect on the human agency and collective action.
- *Differences due to players' diversity:* The game sessions were organized via open invitation at Technische Universität Dresden and in international conferences. This allowed people from different countries, ages, and academic backgrounds to participate but did not allow for direct control of the participants. While MAHIZ was developed as a simulation where players take the role of farmers, our qualitative observations indicated that players with a higher pre-existing knowledge of agriculture and irrigation exhibited more strategic behavior and collective action dynamics emerged earlier in the game. While players were from different countries, we did not collect demographic data and did not specifically test for controls over players' strategy or outcomes.
- *Egalitarian situation:* The board game simulates an unrealistic situation where all players start with the same economic resources. In practice, farmers have different conditions like availability of resources and technologies, wealth, and social responsibilities, which may affect their decision-making.
- *Structure of Debriefing:* The debriefings consisted of circular and open-ended questions related to the key learning objectives and explore the players' frame of mind in relation to their strategy and behavior. Nevertheless, in some of the longer game sessions, the written feedback form and oral debriefing were too much for players, which may have affected self-assessment. In future iterations, recording the debriefings and shortening game length could improve the evaluation of the new knowledge generated by the game.

These limitations will be addressed through future work (preliminary results [57]). Specifically, we plan to test the applicability of MAHIZ to socio-hydrological modeling through the development of an ABM to analyze agricultural water demand and the impacts on crop water productivity. This work includes integrating behavior theories into an ABM using a multi-criteria optimization model [58], optimized irrigation strategies [59], and decision-making parameters identified by game sessions with real farmers.

5. Conclusions

Research shows the need to expand the diversity in decision-making processes and therefore the theoretical basis for modeling in complex agrohydrological systems. MAHIZ was developed to analyze socio-hydrological dynamics in a theoretical agrohydrological scenario and to foster social

learning. We found that MAHIZ was both an effective Efs approach to learn about the tragedy of commons in agrohydrology and a potential tool to collect data regarding decision-making processes. Four heuristics, previously applied in broader socio-ecological modeling, were identified in MAHIZ players. These results show that diverse behavior theories can emerge within a serious game, providing a promising potential data source to better explore diverse real-world scenarios such as the effects of policies and climate variability while at the same time advancing education, science communication, and outreach. We also identify relationships between social parameters and the evolution of collective action, including a high symmetric association between communication and trust. Both parameters are necessary for collective action and social innovation. Due to MAHIZ's open game design, our serious game can be adapted for place-based studies to explore the decision-making process with local stakeholders and is a potential new tool for social and hydrological scientists to find relevant decision-making processes and parameters in agrohydrological systems.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/13/5301/s1>, The supplementary material consists of three parts: (A) The MAHIZ Rule Book, (B) Summary of play-testing and recorded game sessions, (C) Feedback form to be fill out at the end of the game.

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Abbreviations

The following abbreviations are used more than once in this manuscript:

ABM	Agent-Based Models
HE	Homo economicus Theory
BR	Bounded Rationality Theory
TPB	Theory of Planned Behavior
HL	Habitual Learning Theory
DN	Descriptive Norm Theory
PT	Prospect Theory
Efs	Education for Sustainability
TGD	Triadic Game Design
CM	Communication
T	Trust
CP	Competence

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