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Optimization of Agro-Socio-Hydrological Networks under Water Scarcity Conditions

Inter- and Trans-disciplinary Approaches for Sustainable Water Resources Management.

Dissertation by

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List of Publications

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To **Franzi**.

For her love, patience, strength, and unconditional support.

Forevermore.

"The history of mankind can be written in terms of human interactions and interrelations with water."

History of Hydrology by Asit K. Biswas (1970)

Acknowledgments

Abstract

Sustainable agriculture is one of the greatest challenges of our time. The pathways to sustainable agriculture consist of successive decisions for optimization that are often a matter of negotiation as resources are shared at all levels. This work essentially comprises three research projects with novel inter- and transdisciplinary methods to better understand and optimize agricultural water management under water scarcity conditions.

In the first project, climate variability in the US Corn Belt was analyzed with a focus on deficit irrigation to find the optimal irrigation strategies for possible future changes. Two optimization methods for deficit irrigation showed positive water savings and yield increases in the predicted water scarcity scenarios.

In the second project, a serious board game was developed and game sessions were carried out to simulate the complex decision space of actors in irrigated agriculture under climate and groundwater variability. The aim of the game was to understand how decisions are made by actors by observing the course of the game and linking these results to common behavioral theories implemented in socio-ecological models.

In the third project, two frameworks based on innovation theories and agro-social-hydrological networks were developed and tested using agent-based models. In the first framework, centralized and decentralized irrigation management in Kansas US was compared to observe the development of collective action and the innovation diffusion of sustainable irrigation strategies. The second framework analyzed different decision processes to perform a sensitivity analysis of innovation implementation, groundwater abstraction and saline water intrusion in the Al Batinah region in Oman. Both frameworks allowed the evaluation of diverse behavior theories and decision-making parameters to find the optimal irrigation management and the impact of diverse socio-ecological policies.

Inter- and Trans-disciplinary simulations of the interactions between human decisions and water systems, like the ones presented in here, improve the understanding of irrigation systems as anthropogenic landscapes in socio-economic and ecological contexts. The joint application of statistical and participatory approaches enables different but complementary perspectives that allow for a multidimensional analysis of irrigation strategies and water resources management.

Zusammenfassung

Eine nachhaltige Landwirtschaft ist eine der größten Herausforderungen unserer Zeit und um diese zu erreichen müssen verschiedene Optimierungsentscheidungen getroffen werden. Da Ressourcen auf allen Ebenen geteilt werden, sind diese Entscheidungen oft Gegenstand von Abwägungen und Verhandlungen. Diese Arbeit umfasst drei Forschungsprojekte, welche mit neuartigen inter- und transdisziplinären Methoden entwickelt wurden, um ein besseres Verständnis des landwirtschaftlichen Wassermanagements unter Wasserknappheitsbedingungen zu entwickeln und dieses zu optimieren.

Im ersten Projekt wurde eine Defizitbewässerung unter Klimavariabilitätsbedingungen im US-Maisgürtel analysiert, um die optimalen Bewässerungsstrategien für mögliche zukünftige Veränderungen zu finden. Zwei Optimierungsmethoden für die Defizitbewässerung zeigten Ertragssteigerungen bei gleichzeitigen Wassereinsparungen unter vorhergesagten Wasserknappheitsszenarien.

Im zweiten Projekt wurde ein Serious Board Game entwickelt, um den komplexen Entscheidungsraum der Akteure bei der Bewässerung in der Landwirtschaft unter sich änderten Klima- und Grundwasserbedingungen zu simulieren. Ziel des Spiels war es, durch Beobachtung des Spielverlaufs zu verstehen, wie Akteure Entscheidungen treffen. Diese Ergebnisse wurden anschließend mit gängigen Verhaltenstheorien von sozio-ökologischen Modellen verglichen.

Im dritten Projekt wurden zwei agentenbasierende Modelle, aufbauend auf Innovationstheorien in agro-sozial-hydrologischen Netzwerken, entwickelt. Im ersten Modell wurde ein zentralisiertes und ein dezentrales Bewässerungsmanagement in Kansas, USA, miteinander verglichen, um die Entstehung von kollektivem Handeln und die Innovationsdiffusion von nachhaltigen Bewässerungsstrategien zu beobachten. Das zweite Modell analysierte verschiedene Entscheidungsprozesse, um eine Sensitivitätsanalyse der Innovationsimplementierung, der Grundwasserentnahme und der Salzwasserintrusion in der Region Al Batinah in Oman, durchzuführen. Beide Modelle erlaubten die Bewertung verschiedener Verhaltenstheorien und Entscheidungsparameter, um das optimale Bewässerungsmanagement und die Auswirkungen verschiedener sozio-ökologischer Richtlinien zu ermitteln.

Inter- und transdisziplinäre Modelle, welche die Wechselwirkungen zwischen menschlichen Entscheidungen und Wassersystemen untersuchen, wie sie hier vorgestellt wurden, führen zu einem besseren Verständnis von Bewässerungssystemen als anthropogene Landschaften in einem sozioökonomischen und ökologischen Kontext. Die gemeinsame Anwendung von statistischen und partizipativen Ansätzen ermöglicht unterschiedliche, aber komplementäre Perspektiven, die eine multidimensionale Analyse von Bewässerungsstrategien und Wasserressourcenmanagement erlauben.

Contents

List of Figures

List of Tables

List of Abbreviations

A-H	Agro-Hydrological
A-S-H	Agro-Social-Hydrological
ABM	Agent-Based Model
APPM	Assessment, Prognoses, Planning and Management tool
BR	Bounded Rationality Theory
ComMod	Companion Modelling
CMA-ES	Evolution Strategy with Covariance Matrix Adaptation
CWPF	Crop-Water Production Function
DN	Descriptive Norm Theory
DInKa	Diffusion of Innovation in Kansas
DIT	Deficit Irrigation Toolbox
GET-OPTIS	Global Evolutionary Technique for Optimal Irrigation Scheduling
HL	Habitual Learning Theory
HE	Homo Economicus
IWRM	Integrated Water Resources Management
MoHuB	Modelling Human Behavior framework
OCCASION	Optimal Climate Change Adaption Strategies in Irrigation
ODD	Overview, Design concepts, and Details
PT	Prospect Theory
S-H	Socio-Hydrological
SAHIO	Sustainable Agrohydrological Innovation in Oman
SCWPF	Stochastic Crop-Water Production Function
SES	Social-Ecological Systems
SNA	Social Network Analysis
SWB	Soil-Water Balance
TPB	Theory of Planned Behavior
US	United States of America

Chapter 1

INTRODUCTION

1. Introduction

Rapidly growing human populations simultaneously influence and are influenced by the availability of water resources to support life and economic activity [1]. It is estimated that global agricultural production will rise by 60% by 2050 to meet the world's projected demands for food and feed [2]. Nevertheless, water resources are still a paradox, as the resource is scarce, but it is often wasted [3]. Uneven distribution of water in space and time along with negative impacts on the quality of water resources have created significant complexities in managing this resource. Water scarcity, i.e., limited access or availability of the resource, is a global issue that has caused and will cause numerous conflicts in competing interests such as agricultural, industrial, and domestic uses, hydropower generation, recreation, and environmental protection [4, 5]. Meanwhile, the value of water resources itself and the many services it provides has not been fully recognized and hence it has been utilized inefficiently in many places. The improvement of agricultural water productivity is widely considered as the best solution to ensure that future water demand does not exceed water availability [3].

Water resources management decisions ultimately involve competing values, which will only get more prominent with increasing scarcity and security over resources [6]. To date, conventional water resources management is dominated by technocratic approaches that may work well in the short-term but can result in unintended consequences in the long-term [3]. These approaches lack to reflect the dynamic relationship between natural, technical, and social dimensions of human-water systems [7]. The integrated water resources management (IWRM) paradigm requires governments to consider how water resources link different parts of society and how decisions in one sector may affect water users in other sectors, as well as to adopt a participatory and inclusive approach by involving all actors and stakeholders, from all levels, who use and potentially pollute water, so that it is managed equitably and sustainably [8]. Therefore, stakeholder decision-making must then be analyzed as integral and endogenous components of the agricultural network [1], where how risk and innovation (i.e., application of new ideas/methods/solutions that meet new requirements) are perceived determines the actions that people take towards the use of resources potentially creating unexpected effects [9].

1.1 Complex Networks Approach

Networks are systems in which multiple nodes are connected by links. Natural water systems can be described as complex networks consisting of nodes such as sources (e.g., surface and groundwater), demand points (e.g., agriculture), and links that transport water above and below the soil surface and to and from the demand points (e.g., pipes and pumps).

Agricultural water management is a perfect example of a complex network, in which ecological, social, and economic demands interact and evolve simultaneously. Nevertheless, current scientific research and policies are still constrained to a single discipline/sector. To analyze the possible future evolution and the impact of man-made or natural shocks to the agricultural network, a combination of diverse disciplines and methodologies is required where the complexities and interactions are to be analyzed.

During the last decade, much scientific effort has been made to underpin integrative water resources management by providing a theoretical basis with network theory that takes into consideration the hydrological component (e.g., soil, climate, crop phenology), the hydraulic components (e.g., pipe, pumps), and the socio-economic component represented by the stakeholders (farmers, managers, policy-makers, etc.) and dynamic economy. The main goal of the implementation of a complex network approach is to represent these components as nodes and their processes as links where the feedback dynamics, nonlinearity, thresholds, heterogeneity are emphasized [10, 11] and observe their behavior to develop integrative and sustainable management practices.

Improving the complex network's resilience and reducing susceptibility are prime concerns for all stakeholders responsible for the design, operation, and protection of the agricultural management [12]. Optimization of these complex networks, i.e., the identification of robust and resilient management strategies, is not possible until a full understanding of the two-way dynamics between demands particularly under different sources of uncertainty (e.g., climate variability, soil conditions, and market demand) is achieved.

1.2 Research Objectives

Figure 1: Focused transdisciplinary A-S-H network.

While much progress has been made in making quantitative assessments of water scarcity impact in agriculture, there remains a lack of fundamental understanding of the interaction between human-water systems and the impact of water scarcity in this interaction. As a result, the current analytical frameworks cannot capture the emerging dynamics. Furthermore, to close this knowledge gap it is required to combine diverse methodologies in an inter- and trans-disciplinary effort where stakeholder participation is vital.

This research aims to provide scientific insights that can be used to inform IWRM by detecting and understanding the relations between physical and social processes in an Agro-Social-Hydrological (A-S-H) complex network (Figure 1) and the impact of water scarcity on this network. To accomplish this goal, diverse methodologies were developed and analyzed that aimed to answer the following research questions:

1. How will water scarcity impact agricultural production and what are the optimal irrigation adaptation strategies?
2. How to collect data regarding the socio-hydrological dynamics in agriculture?
3. How to simulate agro-socio-hydrological networks to optimize agricultural water management and evaluate policies impact?

Consequently, the main objectives of this research were:

1. Evaluate the impacts of climate variability and compare diverse irrigation strategies.
2. Develop a participatory data collection approach to understand the human-water dynamics in agriculture.
3. Analyze diverse decision-making theories and social parameters in an integrative agricultural network model.

While the ultimate goal of the implemented complex network approach is to integrate all parts of the A-S-H network, this is challenging to achieve in practice. Therefore, the presented projects enhanced different nodes and links to propose effective and integrative frameworks for sustainable agricultural management practices. The cover page for each chapter shows a graphical representation of the focused nodes of the transdisciplinary A-S-H network.

1.3 Thesis Outline

The thesis is organized into six chapters:

- Chapter 1: General introduction to the complex agricultural water network. The specific research questions and objectives are then described in this chapter.
- Chapter 2: An in-depth literature review of the multidisciplinary approaches toward sustainable agricultural water management, focusing on novel transdisciplinary and participatory approaches. The main concepts and definitions of the following chapters are described in this chapter.
- Chapter 3: Summarizes the first selected publication where the hydroclimatic variability experienced and projected throughout the US Corn Belt was analyzed and several irrigation strategies were evaluated to find optimal agricultural management practices.
- Chapter 4: Summarizes the second selected publication where an innovative data collection method was developed based on a serious game to detect the main social parameters towards collective action and evaluated the most common decision-making theories. Additionally, this chapter presents a more in-depth evaluation of collaborative and participatory approaches to improve education for sustainability.
- Chapter 5: Summarizes the third selected publication which describes the development and implementation of two agent-based models of a socio-hydrological system where social innovation diffusion (i.e., how and at what rate a new irrigation strategy spreads)

and diverse behavior theories are applied in a multilevel social network (i.e., network composed of social agents connected by different types of links).

- Chapter 6: Summarizes the main contributions of the overall research project and describes an outlook for further research.

LITERATURE REVIEW

Innovation

Behavior

Management

Economy

Collaboration

Policy

A-S-H Networks

Education

Production

Climate

Irrigation

Resources

Soil

2. Literature Review

2.1 Agro-Hydrological Systems

Agriculture is the largest consumer of water resources, globally it is estimated that about 70% of freshwater abstracted is used to irrigate 25% of the world's croplands which supply 45% of global food [13, 14]. In the last few decades, large-scale irrigation systems have become a major source of water for a large proportion of the world's croplands [15]. Hence, water demand for irrigation purposes is increasing and thus, conflicts about the use of water and allocation are becoming more intense [13].

Agriculture is facing many challenges both in economic terms (i.e., productivity and revenue deficits) and ecological terms (i.e., environmental and health impacts) [16]. Researchers, in specific agrohydrologists, have focused on the evaluation of the two-way influence of available water resources and land management practices, and the development of conservation practices [17]. The leading scientific approach to achieve this optimization is the development and implementation of water demand management practices with the main goal of increasing the resilience of agrohydrological systems [18]. These practices have multiple benefits, like deferring new costly water supply infrastructure, promoting water use efficiency, and increasing public awareness. However, the lack of integrated knowledge (i.e., multiple objectives) and behavior heterogeneity of stakeholders hinder the adoption of these optimized practices.
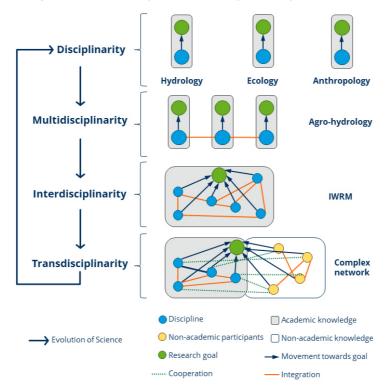
Previous research evaluated the main factors correlated with water scarcity and consequent conservation behavior [19]. For example, reviews by Ervin and Ervin [20], Gould et al. [21], and Traore et al. [22] found that both physical (i.e. soil, crop, recharge) and social (i.e. education level, years of experience, etc.) characteristics are positively correlated with the degree to which farmers perceive of agrohydrological problems (e.g. soil erosion, climate change impacts, degraded water quality.). Recent reviews by Knowler and Bradshaw [23] and Prokopy et al. [24] found the critical parameters for successful adoption of conservation practices in agriculture, i.e., education, income, farm size, environmental awareness, water access, and land ownership. Recent research by Chouinard et al. [25] found that farmers are driven by a "meta-utility" that seeks to balance motives of self-interest with non-egoistic motives related to community and environmental well-being.

2.1.1 Necessary Disciplinary Convergence

As previous research has highlighted, the interdisciplinary nature of managing complex agrohydrological systems requires methods that integrate the technical, economic, environmental, and social aspects into comprehensive frameworks [26]. In this regard, science in general, agrohydrology in particular, is being challenged by a necessary disciplinary convergence (Figure 2), i.e., multi-, inter-, and trans-disciplinarity, to tackle scientific and societal challenges that exist at the interfaces of multiple fields [27]. The diverse disciplinary convergence is increasingly used in the literature and refers to the involvement of multiple disciplines to varying degrees on the same continuum, yet it is ambiguously defined and interchangeably used.

There is growing recognition that different types of expertise are needed, and among the most cited of these are the concepts of inter- and trans-disciplinarity research. For this research project,

the goal was to develop a comprehensive transdisciplinary framework towards sustainable agricultural water management which requires multi-objective optimization.

Figure 2: Disciplinary convergence and evolution of science.

2.1.2 Multi-Objective Optimization Approaches

Multi-objective modeling aims to handle problems that simultaneously need to optimize not just one objective function, but several. These techniques include multi-targeting optimization, Pareto analysis, and fuzzy optimization. Multi-objective optimization approaches integrate different system processes into a combined framework. These approaches are considered to be useful tools to understand the complex interaction between social and ecological processes and to evaluate how these responds to various changes [28]. Within the last decade, significant progress has been made concerning interdisciplinary investigation and modeling of coupled social-ecological systems (SES) [29]. These approaches include combining material or energy flows and economic flows, modeling social behavior and drivers that specifically impact on an ecosystem service, and identifying and modeling specific goods that are relevant for the social system as well as for the ecological system.

Integrated modeling frameworks currently used to optimize agrohydrological systems mainly focus on the irrigation-induced aquifer depletion and its economic impacts [30]. There are two main types of optimization approaches **centralized** and **decentralized** management. The centralized perspective usually refers to a command-and-control process in which a central unit collects all necessary information and makes decisions for each user to achieve better system performance. The decentralized perspective generally stands for a bottom-up procedure in which each user makes individual decisions based on their information and then all individual decisions merge to form the system's overall performance. The centralized approaches are normally

considered more effective in terms of achieving better system performance, but less effective with regards to participation and compliance levels of users [18]. Most common multi-objective optimization approaches for sustainable agricultural water management follow the centralized approach and focused on two main objectives: the optimization of crop-water productivity and the analysis of climate variability impacts.

2.2 Optimization of Crop-Water Productivity

The overall objective of agricultural water management is to maximize the benefits of water resources to society. This overall objective can further be divided into three specific objectives:

1. **Social equity**: water resources are shared equitably among different users and between uses and the environment.
2. **Economic efficiency**: to achieve maximum benefits from water utilization, including both direct and indirect benefits.
3. **Environmental sustainability**: to ensure the availability of water resources for future users, uses, and the environment.

The valuation of agricultural water use is normally estimated by a crop-water production function (CWPF) because the variability of crop yields for a given amount of irrigation constitutes an economic risk [31]. As an indicator, CWPFs have been used to show the obtainable yield at different levels of applied water. The relationship becomes curvilinear as applied water increases further, due to losses from increased surface evaporation, runoff, and deep percolation. Moreover, local factors, such as soil moisture and irrigation efficiency, can affect the shape. Due to the stochasticity of climatic factors, it is necessary to associate CWPFs with a probability function, in other words, stochastic crop-water production function (SCWPF) [32] that are mainly impacted by climate variability.

Climate variability is defined as variations in the mean state and other statistics of the climate over a given time and spatial scales, beyond individual weather events [33]. This variability may be due to natural internal processes or anthropogenic external factors. A stochastic model of climate variability is considered in which slow changes of climate are explained as the integral response to continuous deviations.

In the context of increasing impacts of climate variability on agricultural systems, greater access to and use of climate information and forecasts has the potential to critically support farmers' efforts to manage and reduce risk, increase profits, and improve short- and long-term irrigation strategies [16].

2.2.1 Irrigation Strategies

The adoption of irrigation technology has increased over the last several decades to improve yields in areas with high climate variability [34]. Irrigation scheduling is conventionally based either on soil water measurement, i.e., the soil moisture is measured to determine the need for irrigation, or by soil-water balance calculations estimated by the change in soil moisture over a period given by the difference between the inputs and the losses [35]. Ultimately, the choice of

irrigation scheduling method depends to a large degree on the objectives of the irrigators and the irrigation system available.

Full irrigation via water application with the crop evapotranspiration requirements method is an effective irrigation practice. In traditional irrigation scheduling, a technique to meet full irrigation, the soil moisture in the root zone is allowed to fluctuate between an upper limit approximating field capacity and the lower limit of the readily accessible water [34].

Deficit irrigation is an irrigation practice whereby a crop is irrigated with an amount of water below the full requirement for optimal plant growth, thereby saving water and minimizing the economic impact on the harvest. By limiting water applications to drought-sensitive growth stages such as the vegetative stages and the late-ripening period, this approach aims to maximize water productivity and to stabilize, rather than maximize yields. The major obstacles are that deficit irrigation involves the use of precision irrigation and some risks associated with the uncertainty of the knowledge required [36].

Common approaches to calculating optimal irrigation schedules involve dynamic programming for the optimization of closed-loop irrigation scheduling problems. An alternative approach is provided by open-loop scheduling techniques such as linear and nonlinear programming [37]. Open-loop optimization is based on forecasts generated by simulation or analytic functions of the water budget and crop production of an irrigation system for an entire growing period in advance. The global evolutionary technique for optimal irrigation scheduling (GET-OPTIS) was developed by Schütze et al. [38], takes into account the influence of the stochastic climate variability to solve the irrigation optimization problem.

2.3 Sustainable Management of A-S-H Networks

Agricultural networks are embedded in wider social-ecological processes that must be considered in any complete discussion of sustainable irrigation practices. Just as climatic profiles and irrigation scheduling will influence the future viability of crops, agricultural governance practices create the conditions that foster sustainable agrohydrological systems [39].

The latest research has highlighted the need for the involvement of stakeholders and experts to support learning and decision-making processes for achieving improved environmental and social outcomes [40, 41]. Nevertheless, the difficulty involved in accounting for social components is attributed to a holistic and mechanistic bias inherited from hydrology. The concept of dynamics proposed by hydrologists is very different from that proposed by social scientists. Some methods have been developed to describe social dynamics (i.e. farmers' decision-making processes) such as the model for actions [42], rule-based models (heuristics and game theory) [43], and activity-based models [44].

The current scientific challenge is to look for pragmatic ways to link the analysis of social dynamics with the understanding of the hydrological processes. This requires hydrology to open up further to different approaches and methods used in other scientific disciplines, especially social sciences. This could lead to a transdisciplinary innovative way of conceiving and representing A-S-H networks. Many disciplines have developed their frame of reference for the analysis of natural resources management, for example, in the fields of common-pool resources management [45],

complex adaptive systems [46], the resilience of social and ecological systems [47], or for the hydro-social cycle by critical geographers and political ecologists [48].

2.3.1 Socio-Hydrology

The Scientific Decade 2013–2022 of the International Association of Hydrological Sciences, entitled "Panta Rhei—Everything Flows" has dedicated to improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems [49, 50]. Panta Rhei researchers proposed socio-hydrology (Figure 3) as a use-inspired scientific discipline that entails the study of real-world systems across gradients of climate, socioeconomic status, ecological degradation, and human management [51].
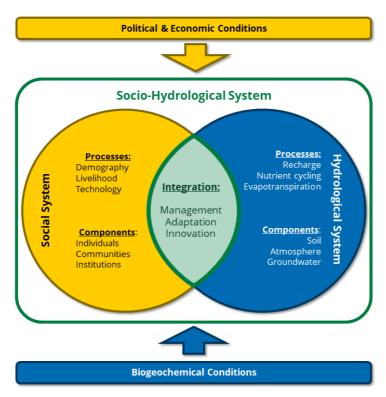
Figure 3: Socio-hydrological system.

The focus of socio-hydrology is on understanding why certain water management outcomes arise rather than proposing centralized management solutions [3] because it treats society as an endogenous part of the water cycle and studies not only the impact of people on the water but also of water on people [52]. This results in a better understanding of long-term developments, predictions, and support for new water management. The most frequent socio-hydrology approach proposed in literature is based on multi-objective modeling frameworks in which variables depicting human behavior interact with hydrological variables [9, 41]. The social component is represented by a set of variables and relations among them, together with hydrological variables that can be translated into equations. A key benefit of the socio-hydrology framework is that it allows a structured and consistent comparative analysis of diverse case studies across contexts, thereby facilitating the discovery of generalizable patterns [5]. However, these approaches remain limited in their potential to support theory on their own because they

are often limited by extensive data requirements and concerns related to the transferability of modeled outcomes [53].

2.3.2 Representation of Decision-Making Processes

The social component has been incorporated into socio-hydrological models as adaptive decision-making processes [54]. Adaptation refers to the development and implementation of innovation in A-S-H networks in response to actual or expected changes [55].

In the early 1980s, Petit [56] developed the theory of the farmer's adaptive behavior that claims that farmers have a permanent capacity for adaptation. Another important concept in the scientific literature is the concept of the adaptive capability to resist evolving stresses and adjust its practices to moderate or offset damages [57]. Holling [58] proposed a general framework to represent the dynamics of a socio-ecological system based on the permanent need to keep adaptation capability under uncertainty, in which dynamics are represented as a sequence of adaptive cycles. There are three main approaches to simulate these adaptive capabilities in socio-hydrology (i) game theory models, (ii) agent-based models (ABM), (iii) participatory modeling [1].

Theory	Definition
Satisficing theory [59]	It assumes that the decision-makers have an aspiration level. They sequentially assess their choice options and stop the search for better options as soon as they have found one that meets their aspiration level.
Values–beliefs–norms theory [60]	Grounded firmly in social–psychological theory and has been empirically tested as a framework for understanding how cultural factors shape environmental decision-making.
Belief–desire–intention theory [61]	Model of human practical reasoning as a way of explaining the future-directed intention.

Table 1: Models of decision formation commonly used in socio-ecological models.

The establishment and successful management of an irrigation system is affected by the governance mechanism and the collective actions of users. Numerous studies find that modern irrigation systems rely on cooperation among various stakeholders [15]. Until very recently, most models of human behavior (i.e., representation of decision-making processes) have been based on the overly simplistic view originating from economics also known as homo economicus [62]. However, the key assumptions of this theory (i.e., perfect knowledge, stable preferences, selfishness, and utility maximization) are in contrast with empirical observations of how people make decisions concerning natural resource use. Humans are not optimization algorithms. We do not always act on their plans and have limited self-control. Since the early 1950s economist and political scientists pointed out that our cognitive capacities are limited, restricting our capacity for utility maximization. We are also intrinsically pro-social, socially, and culturally part of the biosphere. To identify the reasons behind this social paradox, understanding the indigenous and

psychological factors (i.e., attitudes, beliefs, social norms, desires, etc.) of water users' behavior is necessary [63]. Table 1 shows common theories that have been implemented in SES models.

Few model simulations like the model of the global policy response to climate change by Janssen and de Vries [64] determined decisions as a weighted average of the individual decision of agents based on their worldview and the experience with previous implementations. Some of the most prominent theories include economic theory coupled with resource dynamics [65] capture aggregated responses in feedback loops [66], or use ad-hoc assumptions [67]. The challenges in selecting alternative theories into socio-ecological models are (i) the wide range of theories across disciplines, (ii) some of these theories focused on very detailed and narrow aspects, while others are very broad and comprehensive, (iii) there is diverse formalization (experimental, conceptual, empirical) methodologies, (iv) natural and social systems variate in different time scales which require an understanding of causal mechanisms by making assumptions.

Agricultural decision-making models often focus on behavior assumptions of long-term exit and entry decisions [68]. A recent review by Huber et al. [69] identified several key properties of farmers' decision-making, which include (i) the multi-output nature of production; (ii) the importance of non-agricultural activities; (iii) heterogeneous farmers' characteristics; and (iv) the need for concurrent short- and long-term decision-making. However, the reviewed models failed to represent the farmers' emotions, values, learning, risk, uncertainty, or impact of complex social interactions.
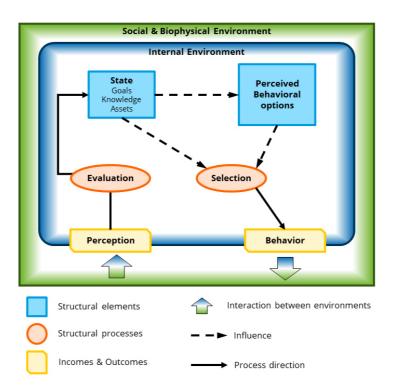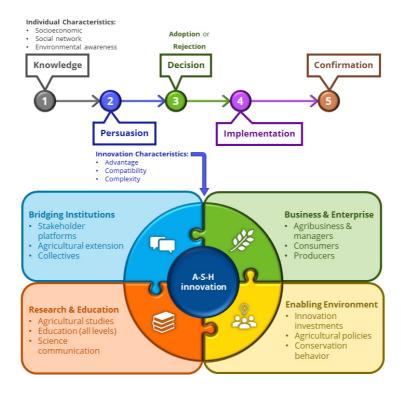
Figure 4: MoHuB framework.

Even when there is increasing recognition of the importance of implementing a more realistic decision-making representation into models. Modelers face the challenge to choose the right decision-making theory for their specific location and multi-objective optimization because any chosen theory will not specify all aspects of the decision-making and require additional

assumptions and data. Therefore, research has focused on implementing different behavioral theories into SES models, which will allow for sensitivity analysis of resource management outcomes, assessment of the consequences of management strategies, and help design better policies [53, 70].

To facilitate the implementation of diverse behavior theories, Schülter et al. [71] designed the Modeling Human Behavior (MoHuB) framework where the decision-making process is decomposed in (i) what goes in (perception), (ii) the rules of selection and evaluation, and (iii) what goes out (behavior). As shown in Figure 4, the framework consists of two main decision environments: the social and biophysical environment and the internal one. The latter is formed by structural elements (state and perceived behavioral options) and internal processes (selection and evaluation).

2.3.3 Influence of Social Network

Figure 5: Steps of the diffusion of agricultural innovation.

An individual's behavior is not only influenced by the incentive of their economic interests but also influenced by other individuals in their social network, creating a process is called social innovation [72]. Such influences have been referred to as, among many other terms, neighborhood effects. In the formation of cooperation, neighborhood effects occur in the channels of information transmission. Individuals who are uncertain about the expected payoffs tend to use information from others (social comparison or imitation) instead of relying on their information (deliberation or repetition).

Social Network Analysis (SNA) is a field that studies the characterization and analysis of social structure and interaction through network representations, traditionally, focused on static networks (i.e., networks that do not change their structure over time). Recently, much progress

has been made in understanding the processes of growth and change of real-world networks [73]. Dynamic SNA is a new field that incorporates the mechanisms of network growth and change based on agent interaction processes.

Innovation is an important concept for the development of sustainable agriculture practices. The development and adoption of agricultural innovations interact with the main parts (economic, social, environmental) of sustainability. Figure 5 shows the diffusion of innovation by Rogers [74] and the intersections necessary for A-S-H innovation [75] which strongly depend on the social, institutional system behind the conservation technological features of the innovation. The analysis of the drivers of the innovation diffusion in agriculture is therefore a very interesting topic for studies of shocks and resilience in networks.

2.4 Socio-Hydrological Modeling Approaches

2.4.1 Game Theory Approach

Because water allocation is a problem involving multiple stakeholders with different interests, conflicts usually arise that require negotiations and cooperation to find an optimal resolution. Game theory, a powerful tool for negotiation modeling, is the mathematical analysis of the interaction between players, where the amount of payoff that a player receives is dependent on the player's own decision, as well as the decisions of the other players [76].

Game theory models implicitly specify the rules of the game [77]. There are two ways to determine the cooperation in the game:

- **Non-cooperative game theory**: actors adopt a self-optimizing attitude to meet their objectives and derive stable outcomes as equilibria [78].
- **Cooperative game theory**: actors have a willingness to communicate, coordinate actions, and pool resources [79].

A game can be repeated several times, also known as the evolutionary game-theoretic approach, where actors adapt their strategy based on the decisions of the other players in the past and future [76, 80]. Game theory models assume a constant population size and play out until some steady-state value is obtained [81]. Game theory outcomes often differ from results suggested by multi-objective optimization methods which assume all parties are willing to act towards the best system-wide outcome and know exactly what options exist and what the corresponding costs and benefits are. Hence these outcomes are closer to practice because reflects the behaviors of the involved actors [78].

The most common implementation of game theory in water resources is the **Tragedy of Commons** by Hardin [82], which describes situations where people share resources and external intervention is needed to avoid resource overexploitation [83]. The leading explanation for overexploitation of common-pool resources is a phenomenon documented extensively at the aggregate level called free riding, i.e., when an individual makes a personal gain far greater than the loss that he incurs as a member of the community [84]. Nevertheless, extensive studies have argued that people are pro-social and that humans are uniquely altruistic, willingly sacrificing their welfare to benefit others [85]. An alternative explanation for free-riding is that individuals are trying to maximize their financial gain, but they are not playing the game perfectly [86]. This

hypothesis predicts individuals initially cooperate to some degree because they are uncertain or they are mistaken about how the payoffs operate, or perhaps they operate a heuristic from every-day life that starts off cooperating without calculating the consequences [87].

Recent studies about game theory and irrigation are related one way or another with social learning and adapting behavior. For example, Finger and Borer [88] applied game theory to identify the factors contributing to the continuation of traditional irrigation systems in Switzerland even though irrigation is no longer profitable. Kimmich [89] associated groundwater irrigation with electricity policies for irrigation in India and depicted social learning as a sequential nested coordination game.

Although modeling can help understand the complex interaction between human and nature, the previous studies have not been able to simulate this system precisely due to the lack of suitable mathematical models for the analysis of systems with self-optimizing stakeholders, and the lack of information about the properties and behavior of the stakeholders in common-pool resource systems due to the absence of the detailed regulatory system [90]. In recent years, top-down approaches are being replaced by bottom-up approaches in water resources like ABM.

2.4.2 Agent-Based Modeling

Previous approaches have developed Bayesian networks [28] with limited data from this region at a farm-scale to analyze the links between the hydrological and socio-economic processes. However, these Bayesian networks use discrete sates rather than probability distributions, which leads to misinformed modeling results. Bayesian networks require high-quality input data to estimate the linkages which make the assessment very computationally expensive and are acyclic, and thus do not support feedback loops. Additionally, Bayesian networks only capture casual relationships between the specified variables, which limits the capabilities to estimate correlations between A-S-H processes that show complex behavior.

The power of ABMs comes from the most basic technique for tackling any complex problem which is to divide it into smaller, more manageable chunks [91]. ABMs provide a tool to represent the human decision-making process explicitly and simulate agents' actual behaviors by delineating interactions among them.

The use of ABMs approaches to optimize agricultural policies has been progressively increasing over the last few years [69, 92]. The major advantages of ABMs include:

- Representation of the different conflicting interests and goals of different agents resulting in more natural and transparent descriptions of the systems where the bidirectional relationship between the individuals and the system and the emergent behavior can be modeled;
- Robustness against failure with distributed control and responsibilities;
- Scalability through easy agent addition and modification;
- Accommodation of uncertainty and dynamics of the task environment due to explicit representations of geographical environments.

An agent-based model typically contains five main components [93] as shown in Figure 6

1. A set of agents with heterogeneous attributes;
2. Decision methods that control how agents update their attributes;
3. Adaptation of the involved social and environmental systems;
4. Interaction mechanism of when, how, and with whom agents interact;
5. An environment in which agents are located.
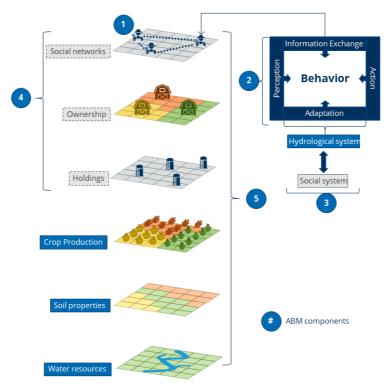
Figure 6: Common socio-hydrological ABM components.

The characteristics of the software are crucially important in assuring the success of formalizing ABMs. The best way to improve the quality of modeling is to choose object-oriented programming. This choice simplifies the translation of the problem into a set of agents and events, and these become objects and steps activated by loops in the model. The Overview, Design Concepts, and Details (ODD) [94] protocol was published in 2006 to standardize the published descriptions of ABMs with the main goal is to make ABMS more understandable and reproducible in different scenarios.

Empirically-oriented ABMs draw on a large number of different data sources to develop and parameterize their agents. Where new data collection is required to inform model and theory development, researchers may consider incorporating social concepts into the experimental design [95]. Behavioral experiments have been used extensively to study factors affecting resource governance [96]. High data requirements have often been cited as an important drawback of ABM; on the other hand, ABMs provide considerable flexibility in the representation of processes, which can be tailored according to the available data. Robinson et al. [97] review data collection approaches for empirical ABMs and classify them into six categories: (i) sample surveys; (ii) participant observation; (iii) field and laboratory experiments; (iv) companion modeling (ComMod); (v) GIS and remotely sensed spatial data; (vi) secondary data sources such as agricultural censuses, farm accounting data, and agronomic data provided by extension services. The strength of novel data collection methods (e.g., games and participatory models) is

the possibility to elucidate behavior that (i) is not easily captured by structured interviews; (ii) cannot be inferred from statistical data; or (iii) does not necessarily comply with standard economic assumptions.

Although it is relatively new modeling approach, ABMs have already become a widely used approach for the analysis, modeling, and simulation of complex A-S-H networks [4]. Kock [98] used ABMs in socio-hydrological systems to investigate the societal effects of incorporating an additional institution to the existing water resources management institutions. Soman et al. [99] developed a multi-ABM to capture multiple farmer typology behaviors in making land-use decisions that affect production. Barthel et al. [100] develop a multi-ABM that simulates the decision-making process of the water supply sector due to the effects of climatic change. Nikolic et al. [101] integrated system dynamics simulation with ABMs to provide support for integrated water resources management through analysis of spatial and temporal dynamics of water resources systems. Berger [102] used ABM to manage agricultural land use and water resources. Recent reviews of implemented ABMs stated that the complex and context-dependent nature of human decision-making resulted in ad-hoc representations of human decisions with certain characteristics (e.g., uncertainty, adaptation, learning, interactions, and heterogeneities of agents) [70]. However, most representations are not explicitly based on a specific theory, and if so, they are mostly based on economic theories.

2.4.3 Participatory Modeling

Stakeholders, non-specialists in most situations, do not easily envision the non-linear links between their decisions and the environmental consequences within the system of interest [11]. Participatory modeling is one tool that can be used to explore potential outcomes and help stakeholders develop their preferences into social values to manage and adapt to environmental change [103]. Public participation can be a means to obtain data from the public, to educate them, and to promote model results and subsequent decisions [52]. Also, it can be a means to involve the public in the modeling itself and give them control over what is modeled exactly and what assumptions are used.

Facilitating formal participation requires investments in better communication as well as building credibility and legitimacy [104]. A range of tools, such as citizen science, role play, serious games, and decision theaters have been adopted in A-S-H modeling to understand actor responses to different environmental states and also educate them about the biophysical implications of their actions.

The literature on participatory approaches considers dialogue and communication as the primary focus to achieve better collaboration among stakeholders [105]. Participatory processes are mainly understood as social or collective learning processes, and many debates in the literature point out the limited ability of such dialogical approaches to deal with situations that are too coercive [106].

Sustainable management deals with the social process leading to an ecological state and with these processes comes a need of interventions, including mediation to resolve conflicts, facilitation of learning, and participatory approaches that involve people in negotiating collective

action. In this context, computer-enhanced modeling becomes a tool for interactive learning instead of a tool to pilot the system.

Companion Modelling (ComMod) [107] is a computer-enhanced participatory modeling approach aimed to facilitate exchange among stakeholders involved in a shared problem of natural resources management. This flexible approach has been applied since 2000 in several cases all over the world. It is based on the iterative co-construction of simulation tools such as role-playing games and agent-based models. It aims to integrate multiple stakeholder perspectives and to enhance the collective exploration of possible scenarios [105]. The different stakeholders, including scientists, work out a common vision on resource management in an interactive fashion that would lead to the identification of new alternatives for action.

2.5 Education for Sustainability

Persuasive communication, education, and involvement of stakeholders are necessary to develop sustainable adaptations [108]. Learning is essential for academic and non-academic disciplines [10]. There is an intricate relationship between the research, teaching material, management practices, and policies [109]. In the modern world, where science, technology, and society are tightly interwoven, all stakeholders must learn sustainable practices and make informed decisions. Social learning is defined as a change in understanding that goes beyond the individual to become situated within wider social communities through social interactions between actors within social networks [110]. This theory mediates learning between stimulus and response. These cognitive processes allow for individuals to learn new behaviors from others through observation [6].

The positive pedagogical impact of experiments has already been documented [111]. By having diverse stakeholders get involved in the kind of decision-making challenges, we can engage them in exploring the difficulties that other stakeholders face in their daily lives, illustrate the human biases and difficulties for making choices when it comes to trade-offs between the present and the future, others and self, or the difference between valuing gains and losses.

2.5.1 Experiential Learning

According to Kolb [112], experience plays an important role in the learning process. Participatory experiments or games expose participants to different learning moments that cater to different learning styles [113]. Participants are exposed to the Kolb's experiential learning four-stage cycle [112]:

1. **Concrete Experience**: participants experience the behavior, different levels of influence and potentially conflicting interests of stakeholders involved in a simulated system, representative of real-life context in many instances;
2. **Reflective Observation**: participants reflect on the outcome and on the challenges they faced.
3. **Conceptualization**: participants identify the challenges discuss the need for stakeholders' collaboration and test participants knowledge

4. **Active Experimentation**: participants practice the concepts they learned in a simulated integrated system, with the potential to further practice later in real-life situations.

With the use of participatory learning approaches, like serious games, the process of acquiring knowledge is enhanced through active practical engagement, socializing, cooperation, repetition, and reflection.

2.5.2 Serious Games

Making science more accessible and interesting to the public through the process of gamification has become increasingly popular in recent years [114]. The idea of using games for purposes other than fun was first formulated in the book Serious Games (Figure 7) by Clark C. Abt [115] as games for educational purposes that are not intended to be played primarily for amusement [116, 117].

Figure 7: Objectives and applications of serious games.

The design of serious games follows the approach of Triadic Game Design introduced by Harteveld [118]. This approach involves a triad consisting of the interdependent worlds of reality, meaning, and play that has to be balanced out during the design process [119]. Studies have indicated that board games are useful learning tools because participants are playing face-to-face and employing specific mechanisms (strategy, cooperation, lying, betrayal) to win. According to previous literature [120], educational board game developers have emphasized knowledge transmission because they possess the following features simultaneously: role-play simulations, goal orientation, procedural rules, feedback mechanisms, player interactions, and repeated process rounds.

Figure 8: Classification of serious games.

Based on the learning objectives, serious games are designed in many different forms and can be played in various techniques (Figure 8). Setting aside genre and narratives, the application of games in a transdisciplinary system focuses on (i) research and collecting information, (ii) learning by practicing and analyzing, and (iii) fostering a change in the target groups' attitude [121].

Metric	Type of learning		
	Traditional	**E-learning**	**Serious games**
Implementation	Moderate	Low	High
Cost	High	Low	Moderate
Proficiency	High	Low	High
Confidence	Moderate	Low	High
Retention	Moderate	Moderate	High
Debriefing	High	Moderate	High
Economic impact	High	Low	High
Level of Engagement	High	Low	High

Table 2: Learning advantages of serious games.

Serious games have become an important tool for participatory research approaches [122] and provide A-S-H studies with a tool to engage with the community in an entertaining, engaging manner, which in turn triggers a process whereby the community and the organization learn and move towards solutions together [96]. The impact of serious games in education [123] (Table 2)

have consistently revealed positive effects on promoting motivation and participation, on exercising creativity, and on forming an environment for multi-criteria skill development.

A recent review by Madani [124] provided an overview of game-based learning and the state of serious games for environmental management, offering insight into their potential as effective tools in facilitating environmental education. Game-based approaches for water governance aim to facilitate understanding of the overall complexity of the real world; foster stakeholder collaboration, cross-sectoral integration, and/or multi-stakeholder dialogue; experiment with multiple scenarios in a safe trial environment, and facilitate social learning [125].

2.6 Summary of Research Gaps

The review of available research and methodologies, several potential research gaps in analyzing and optimizing the resilience of A-S-H networks. These research gaps mainly involve the incorporation of human-water dynamics and the conflicting multi-objective from the components of the network (sustainable management vs profitable outcomes).

In order to develop sustainable water resources management for agriculture, it is necessary to include the participation of stakeholders in the modeling process. While complex computational frameworks like ABM and game theory models have been the focus of sustainability research lately, little development has been done toward the integration of transdisciplinary expertise into these models.

Innovative participatory approaches, like serious games, show a potential opportunity to enhance social learning. Social learning is the primary objective of science co-production that depends on three conditions [126, 127] (i) integration with stakeholders in all phases of research, (ii) transdisciplinarity, which in turn depends on scientists' willingness and low institutional barriers, and (iii) the creation of usable science that directly reflects expressed stakeholder needs and should be understandable, available, and accessible at the times and places to the community.

Chapter 3

IRRIGATION OPTIMIZATION IN THE US CORN BELT

Innovation

Economy

A-S-H Networks

Production

Irrigation

Climate

Resources

Soil

3. Irrigation Optimization in The US Corn Belt

Simulation-based studies of irrigation management often don't consider the variability of important climate parameters within different temporal scales. These studies mostly focused on only rainfed sites or only irrigated sites with assumptions of full-field capacity irrigation.

Current research gap highlights the need for multidisciplinary simulations where different irrigation management strategies for optimized crop production are compared and assessed within different climate variability scenarios. Therefore, based on the projected changes in water resources availability and the potential of implementation of irrigation technologies in the intense agricultural region in the US known as the Corn Belt, the objective of this study was to understand the variability of key hydroclimatic parameters (i.e. temperature, precipitation, and evapotranspiration) at different temporal scales and to evaluate diverse irrigation strategies with their respective optimizers for several locations across the Corn Belt. For this study, the complex network approach focused on an interdisciplinary Agro-Hydrological (A-H) network. Figure 9 shows the experimental design implemented in this study.
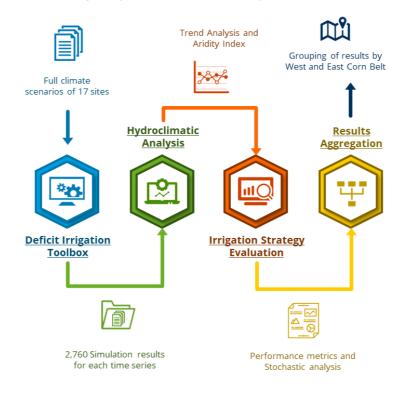
Figure 9: Applied experimental design.

3.1 Agriculture in The Corn Belt

The Corn Belt (Figure 10) is a region in the US Midwest that consists of the states of Iowa, Illinois, Indiana, Nebraska, Kansas, Minnesota, Missouri, South Dakota, North Dakota, Ohio, Wisconsin, and parts of Michigan and Kentucky. The Corn Belt is known for the ideal climate and soil conditions for crop production and intense farming characterized by perfect soil and climatic conditions [128]. Hence, it has dominated the corn production in the US and settles the US as the largest corn producer in the world. The Corn Belt region is comprised of two large basins, the

Upper Mississippi River Basin and Ohio-Tennessee River Basin, which are considered the key contributing areas for the Northern Gulf of Mexico's hypoxic zone. Thus, in this area, it is of utmost importance to ensure that intensive agriculture can coexist with a sustainable water environment [129].

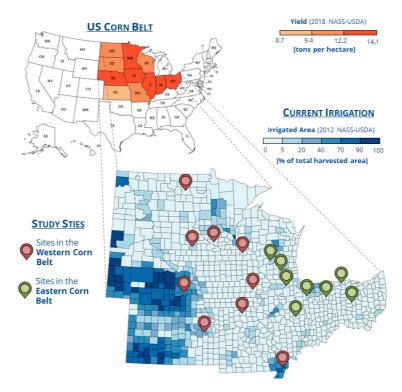**Figure 10**: Map of the US Corn Belt with current irrigated area and location of study sites.

Agricultural production in the Corn Belt is becoming increasingly complex and challenging in the face of a rapidly changing climate and the need to balance growing crop productivity with environmental protection [130]. For agricultural producers in arid regions of the Western Corn Belt, water for irrigation represents a major constraining resource. In response, agricultural producers who depend on irrigation have sought solutions that optimize the value obtained from increasingly limited irrigation water [131].

In this study, county-level data of corn yield and climatic variables for 17 spatially representative sites were evaluated within the Corn Belt. The data was collected from the National Agricultural Statistics Service annual surveys. Because this study focuses on the impacts of climate variability, the yield data were restricted to and detrended from the 30 years averaged yield of each county to decrease the influence of technological changes. The on-site station daily meteorological data for these 17 counties were obtained from the National Climatic Data Center [132]. Climate records for 2041–2070 were projected using the bias-corrected model combination MM5I + HadCM3 [133]. The performed simulations aimed at (i) characterizing the prospective climate and irrigation implementation in the Corn Belt; (ii) evaluating seven irrigation management strategies, ranging from no irrigation to optimized deficit irrigation; and (iii) finding optimal irrigation for each one of the 17 studied sites.

3.2 Historical and Prospective Climatic Variability

Eastern Corn Belt: Baraboo, Beloit, Marysville, Toledo, Huntington, Rensselear, Dekalb, and Tuscola

	Month	April		May		June		July		August		September	
	Time Series	H	F	H	F	H	F	H	F	H	F	H	F
	Max	9.79	9.95	12.25	7.87	14.73	6.75	15.14	6.98	13.14	5.56	10.39	5.34
P	Average	1.86	2.05	1.90	1.34	1.66	1.32	1.20	1.33	1.10	1.46	1.24	1.39
	Min.	0.14	0.15	0.12	0.06	0.07	0.14	0.02	0.11	0.02	0.15	0.03	0.15
	Max	3.87	5.27	4.92	5.38	5.73	4.87	5.90	3.87	5.24	2.97	4.19	2.30
ET	Average	2.78	4.42	3.81	4.45	4.68	3.95	4.86	2.97	4.23	2.14	3.30	1.58
	Min.	1.89	3.12	2.64	3.13	3.49	2.68	3.69	1.79	3.19	1.21	2.44	0.77
	Max	20.46	28.59	25.72	27.75	30.28	25.03	31.68	19.82	30.93	15.42	27.80	12.35
T	Average	9.80	19.31	15.69	18.34	21.01	15.66	22.99	11.00	21.97	6.95	17.79	4.29
	Min.	-0.47	9.70	5.49	9.05	11.07	6.48	13.46	2.36	12.15	-1.40	7.00	-3.45
Western Corn Belt: Brooking, Columbus, Olivia, Rochester, Grand Forks, Iowa City, Kirksville, New Madrid, and Topeka													
	Max	11.90	11.76	16.12	10.08	19.54	9.33	17.78	7.55	16.83	6.32	14.43	5.53
P	Average	0.82	1.11	0.92	0.79	0.95	0.68	0.52	0.60	0.48	0.75	0.60	0.62
	Min.	0.05	0.05	0.01	0.02	0.00	0.01	0.01	0.03	0.00	0.04	0.01	0.02
	Max	4.03	5.82	5.09	6.04	5.48	5.48	6.09	4.50	5.48	3.65	4.35	2.97
ET	Average	2.85	4.62	3.89	4.65	4.17	4.17	4.99	3.14	4.34	2.29	3.26	1.72
	Min.	1.77	3.27	2.57	3.19	3.26	2.69	3.58	1.85	3.09	1.22	2.16	0.81
	Max	23.56	31.54	28.24	31.18	32.45	28.24	34.41	23.27	34.01	19.46	30.19	16.40
T	Average	8.93	17.96	14.58	17.38	19.34	14.94	21.44	10.32	20.41	6.83	15.93	4.20
	Min.	-1.73	9.36	4.70	8.83	10.73	6.01	13.16	0.90	11.82	-2.96	6.11	-5.42

H = Historical Time Series (1981 - 2010), **F** = Future Time Series (2041 - 2070), **P** = Precipitation, **ET** = Evapotranspiration, **T** = Temperature

Table 3: Hydroclimatic variability in the Corn Belt.

The recorded climate data for 1981-2010 was evaluated and compared them to projected data for 2041-2070. Additionally, the recorded irrigation in the studied sites was analyzed. The majority of the sites (Table 3) show increasing trends in temperature in the early season, with average annual temperatures increasing over the last several decades and a shift in seasons with an earlier winter and shorter spring. This shift has led to increased crop transpiration in mid-season and longer growing season dates by around 12 days more than it was a century ago. A slight increase of 5-10% of the average rainfall was found, especially in the mid-season. Additionally, an increase in the amount of short intense rainfall (i.e., flash floods) was found that could severely impact crop production at any stage of the growing season. Previous studies [134] infer that climate change would increase irrigation water consumption by 19% while corn yields would decrease by 7%. Projected 2041–2070 growing season precipitation indicated increased growing season dryness due to rising temperatures and solar radiation. Consequently, as growing season water scarcity becomes more frequent, irrigation systems will provide a viable climate adaptation strategy for agricultural production.

3.3 Simulated Irrigation Strategies

The simulations were based on the decision support tool for Optimal Climate Change Adaption Strategies in Irrigation (OCCASION) [32] that assess limited irrigation systems and the impact of climate variability and derive site-specific stochastic crop-water production functions (SCWPFs).

The stochastic crop-water production functions offer advantages over traditional aggregate empirical models when seeking to model the impact of risk preferences on irrigation demand.

	Name	Definition
Non-optimized strategies	Rainfed	No water application to be used as a reference for the lowest limit of yields
	Full supplemental irrigation	Application of a predefined amount of water when the soil water deficit is near full capacity.
	Simple Deficit irrigation	Application of a predefined amount of water when the soil water deficit is below a threshold and serves as a reference for the other optimized deficit irrigation strategies.
	Constant supplemental irrigation	Applies a fixed depth of water for a fixed irrigation interval of 7 days
Optimized strategies	Deficit irrigation with decision table	A closed-loop irrigation control based on information about the available water and the water deficit in the soil. The optimizer was implemented using the Evolution Strategy with Covariance Matrix Adaptation (CMA-ES) [135].
	Deficit irrigation with a decision table and phenological stages	Implements a modified decision table based on the crop response to water stress at the specific phenological stages throughout the growing season using CMA-ES.
	Deficit irrigation with GET-OPTIS	An open-loop irrigation control that implements a general irrigation calendar for all growing seasons of the considered time series.

Table 4: Evaluated irrigation strategies.

The implemented framework consists of: (i) a future and historic climate scenario; (ii) the Soil-Water Balance (SWB) model, which was used to estimate the irrigation system during the growing season and the yield response of maize to the considered irrigation management strategies; and (iii) seven irrigation strategies with the specific algorithm for optimal irrigation scheduling with limited water supply. The estimated SCWPFs, which are empirical probability functions where for every volume of applied irrigation water and the specific yield that can be achieved. The irrigation strategies evaluated are shown in Table 4.

3.4 Optimal Irrigation Strategies Throughout the Corn Belt

The main idea was to qualitatively compare the seven irrigation management strategies. Figure 11 shows the results of the optimal irrigation strategies for four different initial soil moisture.

To summarize the main findings: (i) constant supplemental irrigation showed an improvement in yield and small water savings only in wet soil conditions (i.e., above 30% initial soil moisture); (ii)

the decision tables and GET-OPTIS optimizers showed better results within all the studied sites and when compared to non-optimized irrigation strategies; (iii) GET-OPTIS showed better results for wet soil conditions with higher precipitation variability and the Decision Tables performed better for dry soil conditions with high precipitation variability; (iv) in all locations, stochastic variability between years showed to be higher at low levels of irrigation, which was improved by GET-OPTIS and Decision Tables optimizers.
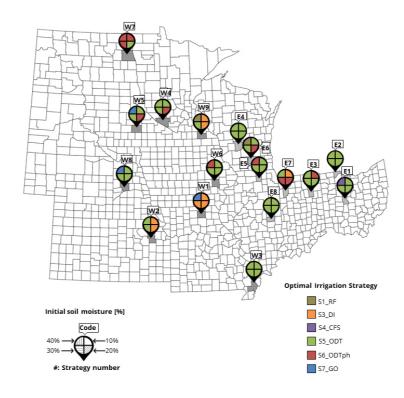

Figure 11: Optimal irrigation strategies for the predicted climate variability.

Irrigation may become a relied-upon a strategy to mitigate potential corn production losses across the Corn Belt, which will impact previously unaffected watersheds and groundwater resources. Irrigation has been adopted primarily in the western states (Kansas, Nebraska, South Dakota, and North Dakota). The results showed that optimized deficit irrigation, especially with the decision table optimizers, would be a potential solution for water scarcity impact in agriculture in these states. Although irrigation technology will not assist with the potential flooding events that could occur more frequently, these systems may provide more stability in the water availability to crops under a more uncertain future climate. Recent studies [30] have shown that irrigation, in general, is expected to remain an unprofitable investment in some of the wettest locations across the Corn Belt, such as eastern Ohio and in Minnesota, and in Iowa, where some of the most fertile soils are located.

3.5 Summary

Identifying irrigation strategies to improve agricultural water use has a pivotal role to play in agricultural innovation development and implementation towards A-S-H network optimization and sustainable water resources management. In this study, the climate variability in the Corn Belt was evaluated and diverse irrigation scheduling strategies were assessed focusing on deficit

irrigation, to find the optimal irrigation strategy for the possible future changes. Two optimizers for deficit irrigation showed positive outcomes in case of new irrigation techniques are to be implemented that will help sustainable water management.

The expansion of irrigation will only take place if commercial, legal, and economic circumstances warrant it. Nevertheless, the evaluation of these non-environmental factors is a good subject for future inquiry. A-S-H innovation in irrigated agriculture, and by extension, the findings in this study, will be greatly influenced by climate variability and farmers' decision making. Human agency, hydrological processes, and hydraulic variables create irrigation together. Combined modeling of interactions between human agency and water fluxes will increase the understanding of irrigation systems, and how they emerge from socioeconomic and environmental contexts [136].

The adoption of the proposed strategies at regional scales or the farm level will be greatly influenced by farmers' objectives, methodological limitations, and financial constraints. Irrigation scheduling can be a complex decision-making process, as it is dependent on several factors, including, but not limited to, knowledge of crop water requirements and yield responses to water, the constraints to and specifics of farm management and agricultural practices, and the limitations (financially and technically) of farmers to adopt and implement viable solutions. The seven irrigation strategies evaluated in this study have their associated merits and limitations and will thus apply to different situations.

Chapter 4

PARTICIPATORY ANALYSIS OF A-S-H DYNAMICS

Behavior

Collaboration

Policy

A-S-H
Networks

Education

Production

Climate

Irrigation

Resources

4. Participatory Analysis of A-S-H Dynamics

As described in the previous study, water crises that farmers and society in general are experiencing, are becoming more complex. As such, they require a more integrated approach in managing water resources that links to different sectors of society. Socio-hydrology is developing an understanding of the interactions and feedback between natural, technical and social processes. This new discipline considers society as an endogenous part of the water cycle and studies not only the impact of people on the water but also of water on people.

The most frequent socio-hydrology approaches are multi-objective models in which variables depicting human behavior interact with hydrological variables. Several steps have already been taken to facilitate the inclusion of behavior theories from multiple disciplines into hydrological simulations.

One of the most recent is the framework of Modeling Human Behavior (MoHuB) [71] (Table 5), which analyzed the implementation of common behavior theories and proposed a framework to implement and compare these theories in socio-ecological models.

| Behavior Theory	Key Assumptions
Homo Economicus (HE)	Actors' goal is self-interested utility maximization and have perfect knowledge and unlimited cognitive capacity for calculating outcomes.
Bounded Rationality Theory (BR)	Actors are goal-oriented, self-interested, and may have cognitive limitations, incomplete or uncertain information about the world, and limited time.
Theory of Planned Behavior (TPB)	Actors' behavior is mediated by intentions and perceived behavioral control. Intentions are based on attitudes, subjective norm, and control beliefs.
Habitual Learning Theory (HL)	Actors' behavior is initially deliberate, and goal directed. Repeatedly obtaining satisfactory rewards reinforces the behavior. The actor will stop automatic behavior **if** need satisfaction drops below a critical level.
Descriptive Norm Theory (DN)	Actors' behavior changes by observing the behavior of others. Observation can take place in an almost subconscious manner or can be more deliberately processed.
Prospect Theory (PT)	Actors have a degree of risk aversion, whereby actors bias decisions towards avoiding loss over chancing a gain.
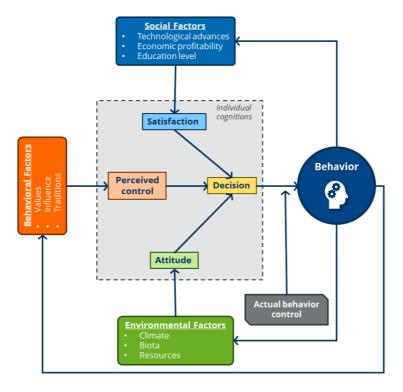
Table 5: Description of MoHuB theories.

Integrating these theories into hydrological models is challenging due to a lack of data for model development and parameterization. A way to collect data and validate these behavior theories is to conduct scenario analysis that incorporates quantitative and qualitative information.

Optimal irrigation scheduling is considered an efficient strategy to improve water productivity in an A-S-H network. The previous study provided a framework to help farmers and researchers in the US Corn Belt finding an optimal irrigation strategy during the expected water scarcity episodes. Nevertheless, the main limitation of a previous interdisciplinary study was that the farmers' decision-making was not taken into account. The objective of this study was to develop a transdisciplinary methodology to collect data regarding the human-water dynamics in agriculture, and thus this complex network approach focused on a theoretical socio-hydrological (S-H) network.

This study focused on the development and evaluation of a serious board game to analyze socio-hydrological dynamics towards collaboration in agriculture. The main objective of the study was to evaluate the serious board game, MAHIZ, for two purposes: (i) as an innovative and enjoyable approach for the general public and (ii) as a data collection method for decision-making processes which can inform socio-hydrological models.
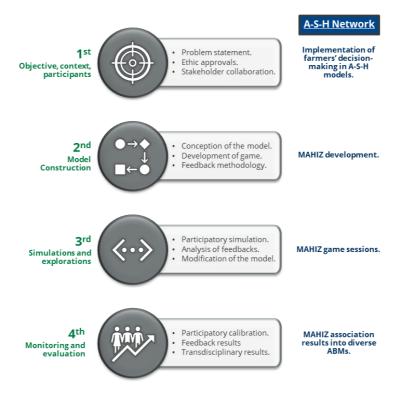
4.1 Decision-Making Processes in A-S-H Networks

Figure 12: Representation of decision-making processes in socio-hydrology.

There is a data gap regarding the social aspects of the decision-making [69] (Figure 12) and also regarding the hesitations of traditional hydrology researchers to explore and implement more complex decision-making processes. Improvements in current water resources management strategies depend on an in-depth understanding of the drivers behind the water use practices of stakeholders [50]. In most simulations, decision-making processes are implemented as settings of exogenous variables or parameters and are not endogenous to the model. In multidisciplinary behavioral economics, the focus has been heuristics and biases, and the framing of decisions [137]. The recent MoHuB framework by Schülter et al. [71] identified the most common behavior

theories and defined their main concepts by decomposing the decision-making process within an individual into three major parts perception, behavior, and rules. Most decision-making theories require high-quality social data that represent the behavioral factors and the dynamics between the social and environmental factors that form the behavior.

4.1.1 Collaborative and Participatory Data Collection Approaches

A possible way to link socio-hydrology to sustainability science is to conduct scenario analysis with the engagement of stakeholders. Scenario analysis is a planning methodology, which incorporates quantitative (modeling) and qualitative (narrative) information to generate possible futures. It provides opportunities for communication to improve public appreciation of science and natural resources since that it can include a set of possible and important uncertainties in the system rather than relying on accurate prediction of a single outcome. In that sense, scenarios can be powerful tools to replace more traditional methods of data collection and to introduce concepts such as resilience in the A-S-H network.

Figure 13: Participatory modeling using ComMod approach.

Narratives are commonly used as data in anthropology, but may not be perceived as valuable data by more traditional hydrology, while data collected via remote sensors might be considered big data source by modelers, but out of context by a typical social science [40].

A common methodology that has gotten a lot of attention lately is the ComMod approach (Figure 13). This approach involves stakeholders in the adaptive development and evaluation of the model's decision-making process. The combination of model simulation and role-playing games is frequently applied. Role-playing games are designed to make use of the simulation and to collect information from the stakeholders and exploring alternatives. The rules and structures of the role-playing games are usually simple to promote player understanding, while the simulations

go into more details. The ComMod approach was implemented in the development of this serious board game.
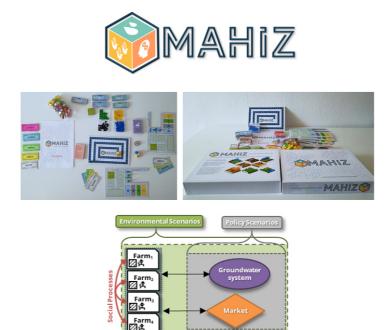
4.2 MAHIZ

4.2.1 Serious Game Development

Figure 14: MAHIZ prototype and the conceptual agrohydrological scenario represented.

A euro-style board game named MAHIZ (Figure 14) was developed that provides a feedback mechanism that allows the player to reflect on their actions and adopt different strategies, stimulates learning, and knowledge retention. MAHIZ offers the opportunity to experience diverse integrated approaches to groundwater management and irrigation strategies. The board game is a scenario analysis of a complex network that has unexpected, dynamic, evolving conditions, and increases the participants' awareness of the context of uncertainty in environmental and decision-making processes. An important challenge in managing common-pool resources is how to ensure collective action to maintain the resource at a sustainable level while preventing individuals in privileged positions from taking advantage of the general effort. The scenarios in MAHIZ, like the drought or flood scenario, were aimed to reflect situations that could occur in real-life and to surprise participants. Experiencing such a setback has been shown to intensify participants' engagement in a game, causing them to more easily remember events and eventually relate them to real-life situations, promoting social learning. MAHIZ rulebook can be found in the Appendix D.

An in-depth monitoring and analysis scheme was used to evaluate the level of active participation and to identify key factors that influence collective action, as expressed indirectly and safely in a gaming context. This scheme consisted of:

1. Post-game surveys;

2. Quantitative and qualitative analysis of communication, trust, and competence during and after the game;
3. Post-game group discussion;
4. Association analysis of data collected regarding behavior theories and social parameters;

4.2.2 Implementation of Serious Game Sessions

From April to December 2019, 35 game sessions (Figure 15) were carried out in Germany, Austria, Czech Republic, Mexico, and the US and to a broad range of expertise of the real agrohydrological system and academic backgrounds participated, from stakeholders (i.e., farmers and managers), observers (i.e., researchers, students, and model developers), and board game developers and aficionados.

Figure 15: MAHIZ sessions.

The main goal of this serious board game was for hydro-science students and researchers to learn and experiment with the diversity of human behavior, thus develop more complex agrohydrology theories and simulations. Additionally, the game aimed to be an intervention tool to (i) raise traditional hydrology researchers and teacher's awareness of the research gap of the lack of variable human decision-making representation in optimization models and to (ii) raise board game developers and aficionado's awareness of the multiple uses of board games in academia and as outreach.

After the game session, players participated in a debriefing where the design of the game and rationality behind their game strategy is discussed. A sample of the feedback form that player filled out is shown in Appendix D.

In most of the game sessions, players learned something new and generated new ideas for agrohydrological simulations as well as other environmental problems that can be analyzed through serious games. This data and observations allowed us to evaluate the learning process of the participants.

MAHIZ was facilitated by a game master who was in charge of introducing the game, controlling time management, and promoting a lively and engaging atmosphere. Other tasks that need to be covered by the facilitating team include: collecting player's post-game surveys, data entry using a dedicated computer interface, feeding back results to players, and keeping track of the nature and verbatim of interactions between players. The game ends with a discussion on various aspects of the game, particularly comparing the outcomes of each of the players. Additionally, the connection between players and their respective influence factors were discussed, as well as the rationale, interactions, and processes behind the group's decisions on agricultural management.

During the development of the methodology, the initial rounds were found to be the most important to observe. When the participants play the game several rounds, they develop more informed decision strategies. Because the main objective is to elucidate decision mechanisms as close as possible to reality in an A-S-H scenario (i.e., a situation of high uncertainty, high time pressure to seize opportunities, and poor understanding of the consequences of the decisions), the first and last few rounds of the game sessions were the most important for the evolution of player's comments and debates arising during the game.

The data collection consisted in two main parts: (i) the evaluation of the learning effectiveness of the board game and (ii) the evaluation of the behavior theories, highlighted by the MoHuB framework regarding the decision-making process experienced by the players during the game. Each player was asked to choose the best-fitted theory to represent the way their decision was formed during the game. This evaluation highlighted within the research community the need to implement diverse behavior theories in agricultural contexts.

4.4 Evaluation of The Learning Process in Serious Games

Parameter	MAHIZ
Classification	Game for Intervention
Target Group	Researchers and game developers
Number of participants per game	4
Repetitions (times played)	+30
Easiness of Play	Easy (90% of participants)
Length (hours)	1.5
Entertainment	Fun (by 91% of participants)
New Knowledge	Yes (by 71% of participants)
New Skills	Yes (by 60% of participants)
Increased creativity	Yes (by 80% of participants)

Table 6: Learning effectiveness assessment of MAHIZ.

The majority of players (Table 6) mentioned that, through the game, they gained a better understanding of the importance of stakeholders' engagement for the successful development and implementation of sustainable agricultural management. Many players, especially researchers, also mentioned that they would be likely to play this game in the future, to support training on the education of sustainability and stakeholder coordination on water management.
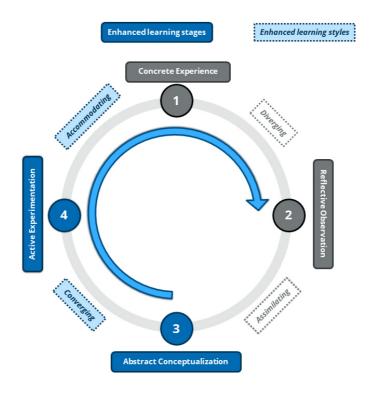

Figure 16: Learning style and stages enhanced by MAHIZ.

The experienced learning process in MAHIZ was form of collaborative learning that happens when individuals practice their skills or knowledge to supplement with other players, hence achieving the outcome they could not have achieved alone, or to the same quality and quantity. Players learned to collaborate, and solve problems through critical thinking and analytical skills. Figure 16 shows the learning process experienced in MAHIZ. Throughout MAHIZ, players learned by abstract conceptualization (i.e., reflection of new scenario and modification of existing concepts) and active experimentation (i.e., trial-and-error application the new concepts). The learning process starts in concrete experience (i.e., encountering a new situation) and ends in active experimentation, were assimilation of knowledge (i.e., concise, rational approach of understanding the overall goal) and convergence of collective knowledge (i.e., finding practical uses for new ideas and theories) was enhanced.

The following key characteristics of serious games were found to be necessary for effective learning:
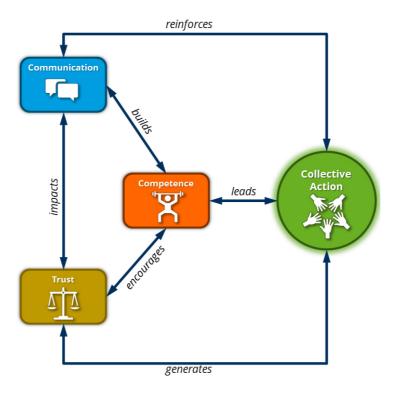
- **Open communication**: providing sustained and open means for interaction between researchers and stakeholders.
- **Minimizing generalizations and fostering common understanding**: exploring discipline-specific assumptions and identifying the diversity of definitions of broad concepts.

- **Leverage diversity**: addressing all points of view in an open, critical way to reveal the most effective sustainable solutions.
- **Leverage unpredictability**: Transdisciplinary gives space and does not over-constraining or control the system.
- **Conscious collaboration**: Careful choice of partners for transdisciplinary innovation projects and the respective disciplines and bias.

The lack of rigorous and standardized methods to evaluate collaborative science projects makes it difficult to assess the real effectiveness of serious games. While the overall feedback of the game sessions was very positive, the long-term knowledge generated from the experience is still unknown. Improved evaluation using both qualitative and quantitative methods would support meaningful analyses and help the development of future serious games and overall collaborative efforts.

Effective transdisciplinary approaches can make an important contribution to the development of this new type of transdisciplinary education which focuses on creating experiences in a fun, motivating, and engaging ways. Additionally, the development of new technologies like video and mobile games, open many opportunities to develop serious games and citizen science projects for a broad public.

4.5 Evaluation of Behavior Theories and Social Parameters

Figure 17: Social factors of collective action.

Measured decision-making factors – communication, trust, and competence – seemed to be positively connected to the smoothness of the trajectory of accumulated additional points.

This study finds communication within the game increased the likelihood of groups reaching sustainable irrigation levels. Figure 17 shows the factors that affected the level of cooperation in the A-S-H network adapted from Ostrom and Walker [138].

Association measures are very useful in understanding relations between different parameters for developing predictive models. Hence the Goodman and Kruskal's τ was used, which is an asymmetric measure of association between two variables is [139]. As a general guideline, a value ranging from 0.1 to 0.4 would be classed as a weak correlation, and anything above 0.5 would be regarded as a strong correlation. A value approaching zero indicates the absence of any association between two variables [140]. The results (Table 7) show that mechanisms related to trust increase the level of cooperation and the range of environmental conditions for which cooperation can evolve. Communication and trust were also positively associated and competence stimulates the development of goals in the decision-making process meanwhile, the leadership of single players conduces to an imposed technology implementation pattern, whereas a process led by several people allows for more consensus building and a diversity of possible outcomes.

	HE	BR	TPB	HL	DN	PT	CM	T	CP
CM	-	+	++	++	++	+		++	+
T	+	+	++	+	-	+	++		+
CP	++	++	++	-	+	++	+	+	

- : no significant association (0 - 0.39) **+** : weak association (0.4 - 0.59) **++** : strong association (0.6 - 1)
T: Trust **CM**: Communication **CP**: Competence

Table 7: Association of social parameters and behavior theories.

4.6 Summary

Social variables beyond the distribution of water resources and other environmental characteristics are necessary to gain a holistic understanding of collective action and innovation development and implementation of A-S-H management practices. Modeling human decision-making in complex natural and human systems remains a combination of science and art and no means an easy task [141].

A serious board game was developed and implemented to learn and teach about the Tragedy of Commons in agriculture. Data was collected regarding the main social parameters that formed the collaboration strategies in the game. Additionally, the players, especially within the hydrologic scientific community, showed an improvement in skill and knowledge level regarding transdisciplinary approaches that are effective social learning techniques. However, attention should be paid to the equifinality (alternative ways of attaining the same outcome) and multi-finality (attaining alternative outcomes from the same inputs) nature of the theoretical A-S-H simulated in MAHIZ. This analysis indicated the key advantages of MAHIZ, including open communication, leverage diversity, and collective action. The results show that irrigation behavior exhibits complex nonlinear responses to changes in groundwater availability.

A wider adoption of collaborative methods is encouraged, both qualitative and quantitative, as well as integrating spatially explicit data and real-time decisions from stakeholders. Doing so will further the understanding of coupled natural and human systems in general, and specifically, help address social conflicts that may arise with the increasing environmental changes.

Chapter 5
ROBUST EVALUATION OF DECISION-MAKING PROCESSES IN A-S-H NETWORKS

5 Robust Evaluation of Decision-Making Processes In A-S-H Networks

As described in the previous chapters, water users are pro-social agents, who have self-awareness about their impact on the environment, can adjust behavior to the diverse changes, and are interconnected through social networks. These interconnections lead to patterns, i.e., cooperation or overexploitation, at the aggregate level. Given the inclusion of conflicting self-governance as an aggregate social process, it is difficult to conduct statistical analysis and obtain high-quality predictions. ABMs are an innovative modeling tool where one can make hypotheses about the behavioral mechanisms, such as social learning (i.e., learning from others in the same social group) and run simulations to test these hypotheses [15] and observe emerging dynamics at individual and aggregated levels.

In this research project, two agent-based models were developed to represent an abstract version of a generic spatial common-pool resource system involving social innovation theories and diverse behavior theories coupled with established agrohydrological models. With the knowledge and data obtained in the MAHIZ's game sessions, these robust frameworks evaluated diverse decision-making processes and heuristics in diverse scenarios with data from Kansas, US, and Al Batinah region in Oman.

The complex network approach implemented in this study focused on a broader A-S-H network, intending to produce effective sensitivity analysis of diverse management strategies and decision-making processes to show how participation and collective action is shaped reflected by speed of innovation diffusion.

5.1 Innovation in A-S-H Networks

Agricultural innovations have to be sustainable in economic, ecological, and social terms, to provide food for the growing global population. As farmers decide which innovations will be implemented in their farms, it is important to understand farmers' decisions on the adoption of multiple agricultural innovations [142]. Previous research (e.g., Knowler and Bradshaw [23] and Prokopy et al. [24]) analyzed the adoption of innovation in agriculture. Respectively, these studies used a vote-count method to review studies on conservation strategies and best management strategies. Nevertheless, these studies focus on local data and specific behaviors and neglect the impact of social networks in common-pool resources.

In terms of studying water scarcity and other extreme climate scenarios, it is relevant to consider the possibilities of agents changing their behavior and the adaptation of specific innovation, which results in changes in social resilience [81]. In the developed models it is assumed that agents can change their behavior in two ways:

1. Formation of public opinion based on the memories and interactions with other agents.
2. Adaptation to extreme climate events.

The following ABMs were based on a cooperative game a la Shapley [143] (i.e., stochastic game where agents act according to strategic rationale, and when their adaptation is driven by diverse behavioral factors) to describe how farmers affect their social network, and how the innovation

of new irrigation strategies is diffused. In these models, farmers make seasonal adjustments to their irrigation strategies while observing changes in others' behavior. Additionally, the innovation diffusion process was simulated by considering the agents' variances of benefits as barriers to adoption. The variances associated with new strategies change as neighbors, friends, and members of the same collective adopt the strategies. Implementation of innovation occurs when an agent's variance of a new strategy is sufficiently reduced, making it worth the risk of adoption.

5.1.1 Multilevel Social Networks

The social network structure is the key to information dissemination and innovation [144]. An innovation network is a social network with specific meanings and objectives for knowledge sharing [145]. The agents in an innovation network are connected in diverse levels, e.g., friendships, neighborhoods, and collectives (Figure 18). Each level of their social networks impacts their accumulation of knowledge and skill level and thus the implementation of innovation [146].

Recent SNA studies have focused on the relationship between innovation network structure and the level of innovation achieved within the network. Previous research by Verspagen and Duysters [147] confirmed that innovation networks based on a strategic collaboration have the small-world property. Therefore, innovation networks can achieve a solution in which resources are allocated optimally [148].
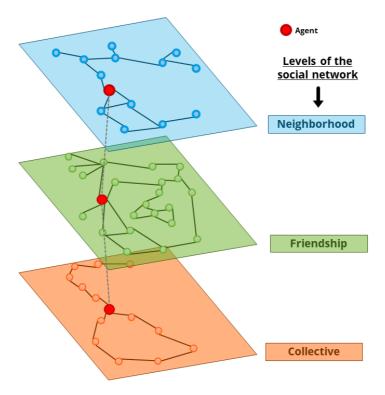
Figure 18: Multilevel social network in A-S-H systems.

Previous studies [72] show the structure and effectiveness of the social networks are informative of the groundwater-usage behavior. At a local level, agents positively react to connected agents sustainably using the resources. Understanding the rules that govern how multilevel social networks are structured, how quickly information is communicated and the kinds of relationships that networks embody are important aspects of the A-S-H network. Empirically measuring

strategic interactions is difficult because identifying the relevant set of a complete social network that a farmer responds to is nearly impossible, and it is hard to distinguish strategic effects from confounding factors.

5.1.2 Theoretical Framework of Developed ABMs

Generally, ABMs explicitly consider the limited knowledge of agents about their environment and let agents take their decisions based on expectations rather than on actual values of key parameters. Previous research [149] suggest that an optimal A-S-H model is not necessarily the one that incorporates all possible variables and factors, but rather, the simplified model whose findings would remain robust to the inclusion of such additional factors.

Both ABMs were developed in GAMA, version 1.8.1 [150] and the implementation code for each ABM is shown in (Appendix A). The interactions in the models take place on a theoretical social network using a random network generator where each edge between a pair of nodes has a fixed probability of being present or absent. The random network was generated by Erdős–Rényi [151] model which assigns an equal probability for every possible edge in a determined level of the social network to occur independently. For each level, there was a different probability.

Figure 19: General framework of developed ABMs.

The developed ABMs (Figure 19) contain various mechanisms for collective action based on communication, trust, and competence. These mechanisms shape the resilience of the system depending on the different management strategies, diverse decision-making theories, and various environmental shocks (i.e., increase of irrigation costs, water scarcity, and saltwater intrusion) which allows measuring whether and how fast the agent population can recover from

these shocks. Additionally, the ABMs work under the Satisficing paradigm with relatively abstract, predefined decision strategies. Agents that are not satisfied with their current strategy start the innovation diffusion process. An agent considers adopting an innovation only if the benefits of the connected agents in their social network that already adopted and/or is satisfied with the innovation is larger than their current benefits (i.e., yield, groundwater, profits, and degree of innovativeness).

5.2 DInKA Model: Irrigation Expansion in Kansas, US
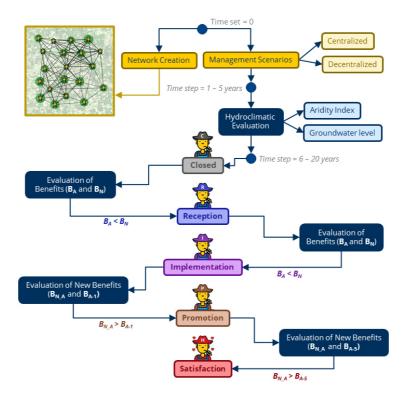
Figure 20: DInKA process overview.

The Diffusion of Innovation in Kansas (DInKA) framework (Figure 20) represents a theoretical irrigation network to examine the efficiency and equity outcomes across different management strategies.

Two scenarios (Table 8) were simulated which consisted of diverse management strategies commonly assumed in centralized and decentralized approaches due to the impact of the interaction.

The main ABM components of DInKa were:

1. **Agents**: 20 farmers as irrigators. It was assumed that all agents are irrigating using the full irrigation strategy and they decide to innovate to optimal deficit irrigation depending on the hydroclimatic variability and the influence from their social network.
2. **Decision-making processes**: As shown in (Figure 20)
   - First step "*Closed*": the agent assesses the hydroclimatic situation based on the aridity index and groundwater level. It was assumed that water scarcity occurs

from the 5th year, where the aridity index is below 0.5 and the groundwater level reaches a critical level.

- Second step *"Reception"*: For the centralized management, 85% of agents start their innovation process and directly move to stage 1 (reception). For the rest of the network and all agents in the decentralized management, each agent assesses their benefits and compares it with the connected agents in their social network. If the agent has better benefits than the average of their social network, then the agent stays in the current stage (closed). Only when the average benefits of the social network are better than the benefits of the agent, they will move to the next stage (reception).

Management	Centralized	Decentralized
Definition	A singular administrator retains total control over all communication and innovation availability of the network.	Each agent within the network functions as a separate administrator with independent decision-making power regarding how it interacts with other agents.
Advantages	Efficiency of the overall system. The network environment is stable and predictable.	Better system reliability. Scaling a network is also easier.
Disadvantages	Networks are not very fault-tolerant. Decisions are made with limited knowledge and faulty communication.	The complex and dynamic nature makes it extremely difficult to build and manage. Same outcomes due to different reasons.
Implementation	Enforced reception to 85% of all agents in the network in year 5. Enforced implementation to 35% of all agents in the network every year after from year 6 to year 20.	No enforced innovation at any time. A random probability (1.5 - 0.5) affects each agent on their calculation of connected agents' benefits.

Table 8: Description of evaluated management strategies and their implementation in DInKa.

- Third step *"Implementation"*: Once the agent is in the reception stage, the agent assesses the innovativeness of their social network, if more than 50% of the connected agents are promoting then they move also to implementation if not the agent re-assess their benefits and the connected agents' benefits. In the decentralized management, the heterogeneity of the communication processes was added as a random probability that affected how the agent perceived the benefits of other agents. If the agent's benefits are better than the average benefits of the social network, then the agent stays in reception. If not, then the

agent starts implementing the optimized deficit irrigation strategy reducing the groundwater extraction.

- Fourth step *"Promotion"*: Once the agent is in the implementation stage, the agent assesses their new benefits and compares it with their past benefits. If the new benefits are better then the agent moves to promotion. If not, then the agent stays in implementation.
- Fifth step "*Satisfaction*": Once the agent is in the promotion stage, there is a satisfaction assessment where the agent assess their benefits to their past benefits (average of 5 years). If the current benefits are better then the agent is satisfied. This satisfaction analysis does not affect the innovation process.

3. **Adaptation processes**: The farmers' intention and behavior will be determined through the satisfying theory and innovation diffusion theory. 30 years of yield, climate (P, T, ET), and profit data were used, as well as CWPF from full irrigation and optimal irrigation strategy from Topeka, Kansas from the simulations presented in (Chapter 3).

4. **Interaction topology**: Interactions directly take place when the agents compare the benefits and evaluate their level of satisfaction on the implementation of deficit irrigation strategies.

5. **Environment**: Multi-level social network with no specific geographical representation.

The hydrological conditions that determine the need for adaptation were represented by: (i) a simple groundwater model [152] was used to estimate a theoretical groundwater level based on the extraction of 20 wells and (ii) the aridity index was calculated as the ratio of precipitation and evapotranspiration.

The agent's benefits (B_A) were estimated as follow:

$$B_A = f(AI, P, Y, CWPF, GL, IS) \tag{5.1}$$

where AI is the aridity index, P is the economic profits of the estimated yield (Y tons/ha), and the irrigated water (CWPF mm), GL is the groundwater level (m) after extraction. The connected agent's benefits (B_N), the new benefits after the implementation of innovation (B_{N_A}) and the previous benefits (B_{A-1} and B_{A-5}) were estimated as follow:

$$B_A = \frac{\sum B_a \ of \ each \ connected \ agent}{N_{connected \ agents}} \tag{5.2}$$

$$B_A = f(new \ P, new \ Y, new \ CWPF, new \ GL) \tag{5.3}$$

$$B_{A-1} = previous \ year \ benefits \tag{5.4}$$

$$B_A = \frac{\sum B_a \ of \ 5 \ previous \ years}{5} \tag{5.5}$$

For the decentralized scenario, the variability in communication (CM), i.e., over or underselling of the innovation, was aggregated as a random probability (0.5 - 1.5) for each agent:

$$B_{N*} = B_N \cdot CM \tag{5.6}$$

5.2.1 Robust Analysis of Innovation Diffusion

Figure 21 shows the innovation stages in each time steps of the simulations. In the first 4 years, the agents are learning from the environment and the efficiency of their current irrigation strategy (closed stage marked in grey). From year 5, after a period of severe water scarcity, the agents start looking for more sustainable irrigation strategies (reception stage marked in blue). As the simulations continue, the agents evaluate their production, environmental impact, and influence in their social media and decide to implement the innovation (implementation stage marked in purple). After this, there is an internal evaluation where the agents access their memory to promote (promotion stage marked in brown) and to evaluate their overall satisfaction with the new irrigation strategy (satisfied stage marked in red).
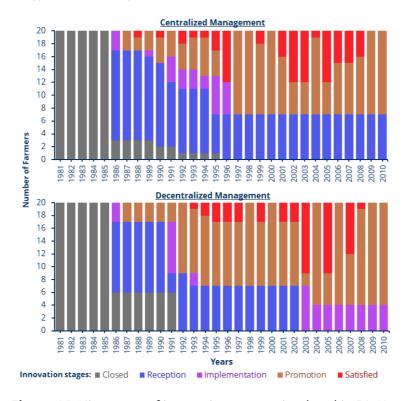
Figure 21: Histogram of innovation stages simulated in DInKa.

The main difference observed from the two scenarios is that the centralized approach showed fewer agents implementing the new irrigation management and thus in water scarcity years tended to over-exploit the groundwater. Nevertheless, the rate of promotion of the innovation was higher than the decentralized approaches. In the centralized approach, the collective action (i.e., year where all simulated agents in the reception stage or forwards) was experienced much later (year 15) showing that the climate variability impacts the over-exploitation of the resources by putting pressure on keeping agricultural production. For the decentralized approach, the collective action was reached earlier (year 11) after experienced 4 years of water scarcity, this agrees with previous studies [153] that show that memory of extreme rain events (i.e., droughts and floods) usually have a 5-year memory time laps in water users. Additionally, the diffusion of innovation in the decentralized approach achieved more agents satisfied with the innovation and a 100% implementation rate in all simulated agents.

This theoretical model is an attempt to answer the question if there is a difference in implementation and system resilience when considering different types of management. Previous research [18] shows that the centralized management is more efficient nevertheless the results show that the users' participation in innovative management practices is critical to achieve a sustainable irrigation scenario. Due to faulty information exchange in a centralized scenario, the efficiency of implementation is overestimated and can only be realistically estimated by taking into account the decision-making process of each agent.

5.3 SAHIO Implementation: Coastal Agriculture in Oman
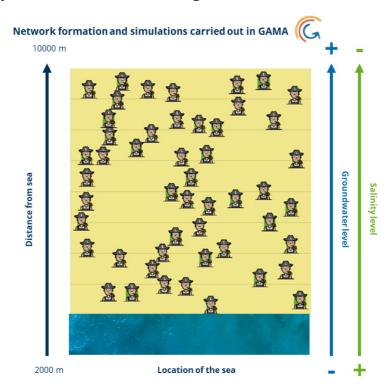
Figure 22: Geographical representation of the farmer's location.

Based on the previous framework DInKa, a more complex yet robust ABM framework was developed for sustainable A-S-H innovation in Oman (SAHIO) that focused only on a decentralized management. This ABM focused on coupling socio-hydrological decision dynamics associated with collective action. In this decision framework, each agent controls its strategy regarding whether or not to innovate their irrigation strategy to conserve water or consume more water to achieve a better economic return based on a baseline allocation scheme. The simulated agents were based on the study population consisted of farmers from the Al Batinah region in Oman (Figure 22) based on the field interviews by Al Khatri et al. [7] where the underlying social networks and processes of the farmers' behaviors have been analyzed. This helped us identify the communication, competence, and trust within the study population.

SAHIO involved the coupling of diverse A-S-H models (Figure 23). Previous simulations using the Deficit Irrigation Toolbox (DIT) [154] and Assessment, Prognoses, Planning, and Management tool (APPM) [155] addressed contradicting objectives, i.e., profit-oriented agriculture vs. sustainable abstraction and estimated optimized groundwater withdrawal scenarios considering saltwater

intrusion. These simulations consisted on 12 farms (300 ha each) in the Al Batinah region and optimized the abstraction rate and irrigation strategy for one farmer located at 5800 m from the sea with four different sustainability indexes (0.51, 0.52, 0.54, and 0.56) in three policy scenarios:

1. **Baseline scenario**: Scenario with 60% irrigation efficiency, full irrigation strategy, and only monoculture agriculture.
2. **Water supply policy**: Scenario where artificial recharge adds 10 million m^3, plus 3 million m^3 of desalinated water, and 2 million m^3 of treated wastewater to the available water, there is a restriction of total abstraction by 40 million m^3, and still, monoculture agriculture is allowed.
3. **Agricultural policy**: In addition to the previous scenario, polyculture production is enforced.
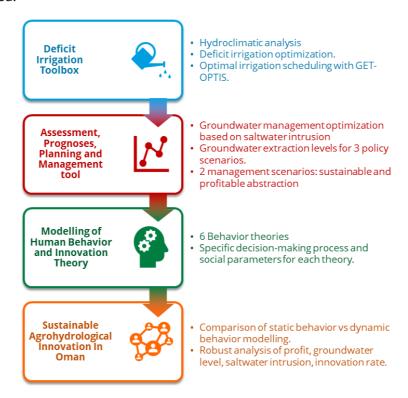
Figure 23: Model coupling implemented in SAHIO.

The results of these simulations consisted of, first for the DIT, the CWPF for diverse crops (maize, tomato, potato, wheat, sorghum, and sugarcane) based on three different irrigation strategies (decision tables, GET-OPTIS, and constant irrigation). Second, the CWPFs obtained with GET-OPTIS were used as data for the APPM, where the profits and abstraction rate were optimized based on the sustainability index for each of the scenarios. The APPM results (profits, costs, irrigated water, groundwater abstraction, and salinity level) of two sustainability indexes were used, which represented the two main management strategies, i.e., sustainable abstraction (0.51) and profitable abstraction (0.54). SAHIO aimed to complement these complex optimizations by analyzing a new scenario where farmers (theoretical representations based on the optimized farmer) must decide which abstraction strategy to implement based on the social and biophysical environment. To simulate the making of this decision, the six theories in the MoHuB framework (Table 4) were evaluated and further implemented the innovation diffusion theory to assess the impact of the decision.
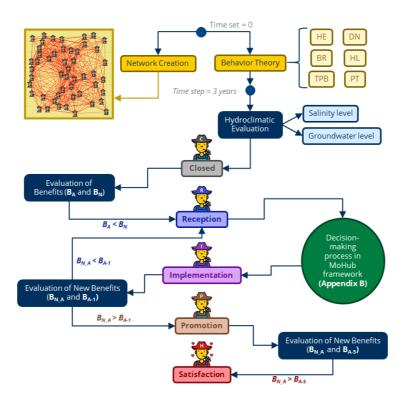
Figure 24: SAHIO process overview.

The main ABM components (Figure 24) of SAHIO were:

1. **Agents**: 50 farmers as irrigators. It was assumed that all agents are irrigating using a profitable abstraction strategy and they decide to change to sustainable abstraction depending on the hydroclimatic variability, saltwater intrusion, and the influence of their social network.

Behavior	Social Parameters		
Theory	Competence	Trust	Communication
HE	High	Efficient	Low
BR	High	Efficient	Efficient
TPB	High	High for collective and Efficient for neighbors and friends.	High
HL	Low	Efficient for collective and High for neighbors and friends.	High
DN	Efficient	Low	High
PT	High	Efficient for collective and friends and Low for neighbors.	Efficient

Table 9: Implemented social parameters.

2. **Decision-making processes**: For scenario policy, the diffusion of innovation for each agent followed the same steps as the decentralized management in DInKA, with the difference that the water scarcity is triggered also by salinity levels in the groundwater

which is based on the theoretical distance from the sea as shown in Figure 22. Additionally, 6 different decision processes with specific social parameters, obtained from the scenario analysis carried out in Chapter 4, were evaluated as shown in Table 9. The decision process for each behavior theory is shown in Appendix B.

3. **Adaptation processes**: The simulation time was 60 years with 3-year periods giving in total 20 timesteps. Every time step, the farmer assesses their network and based on the behavior theory chooses their abstraction strategy. The agent can switch between the strategies (i.e., changing from reception to implementation and vice-versa).
4. **Interaction topology**: Similar to DInKa.
5. **Environment**: Multi-level social network with theoretical geographical representation.

Each of the policy scenarios (i.e., baseline, water and agricultural policy) were simulated with diverse behavior theories and corresponding social parameters to produce a robust sensitivity analysis of heterogeneous decision-making processes and its implications on the resilience of the A-S-H network.

Each of the social parameters affects the benefits calculation of each agent and how they perceived the benefits of the connected agents in their network. The benefits (B_A) were calculated as follow:

$$B_A = f(GW, SL, P, Y) \cdot CP \tag{5.7}$$

$$CP = \begin{cases} High & \rightarrow random\ probability\ (1-1.5) \\ Efficient & \rightarrow 1 \\ Low & \rightarrow random\ probability\ (0.5-1) \end{cases} \tag{5.8}$$

where GW is the groundwater level (m), SL is the salinity level (δS/m), P is the profits ($), and Y is the yield (tons/ha).

As observed in the scenario analysis in Chapter 4 the agent's competence (CP) affects the way they perceived their benefits. When the competence is high, this leads to an overestimation of the actual benefits and therefore overexploitation of the resource. when the competence is low, the agent believes they are in the worse shape and therefore are more open to looking for new strategies. The average benefits of the connected agents (B_N) were calculated as follows:

$$B_N = \frac{\sum B_a\ of\ each\ connected\ agent}{N_{connected\ agents}} \cdot CM \cdot TL \tag{5.9}$$

$$CM = \begin{cases} High & \rightarrow random\ probability\ (1-1.5) \\ Efficient & \rightarrow 1 \\ Low & \rightarrow random\ probability\ (0.5-1) \end{cases} \tag{5.10}$$

$$TL = \begin{cases} High & \rightarrow random\ probability\ (1-1.5) \\ Efficient & \rightarrow 1 \\ Low & \rightarrow random\ probability\ (0.5-1) \end{cases} \tag{5.11}$$

where the communication efficiency (CM) and trust levels (TL) affect the way, the agent perceived the information from the connected agents. The links between agents do not represent perfect knowledge, they represent the amount of information that is available for each agent. The use of random probabilities was used to simulate complete heterogeneous agents and imperfect knowledge diffusion.

5.3.1 SAHIO Sensitivity analysis

The results of SAHIO consist of three main evaluations: the innovation rate, groundwater abstraction (Figure 25) and profits (Figure 26). The innovation in SAHIO was to change from profitable abstraction to sustainable abstraction via collaboration.
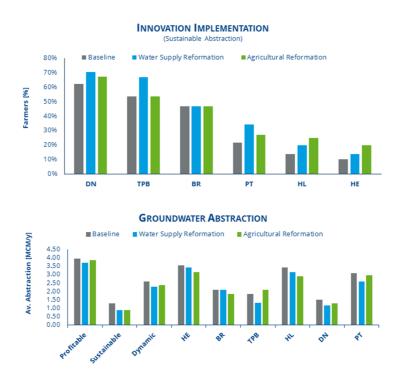
Figure 25: Innovation rate and groundwater abstraction using diverse behavior theories.

Theories that rely in the influence of the social network (theory of planned behavior and descriptive norm) had higher rate of implementation due to the diffusion process. While homo economicus and bounded rationality are both selfish optimizations, the cognitive limitations of bounded rationality have higher impact on the formation of collaboration. However, the policy restrictions had no effect on the rate of implementation. In the case of habitual learning, due to the not constant satisfaction rate, the agents tend to change back to profitable abstraction, leading to low innovation rates.

Another result of SAHIO is the comparison of static vs dynamic behavior. Static behavior is referred to just the sustainable and profitable solutions by the APPM alone. The dynamic results indicate the average of the behavior theories using MoHuB.

When agents are completely rational, habitual learners (HL), or are willing to risk (PT) tended to irrigate more. Whereas the agents with planned rationality (TPB and BR) kept the groundwater abstraction more sustainable in all policy scenarios. Agents with the descriptive norm theory abstracted the least water due to high influence of the social network.
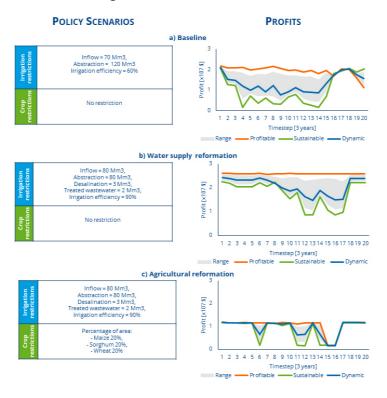
Figure 26: Comparison of profits obtained in the evaluated policy scenarios.

For the evaluation of the different policy scenarios (Figure 26), the range of the profits achieved by all the diverse behavior theories is shown in grey and showing an average dynamic behavior in blue.

When comparing the policies, the availability of diverse sources of water for irrigation was found to increase the profits for the water reformation scenario because the irrigated part of the field was almost doubled using the external water sources. The restrictions on the agricultural reformation policy led to lower profits because monoculture production was not allowed. This policy presents a centralized management, trying to reach an equilibrium between sustainable and profitable outcomes.

The results of the SAHIO show a comparison of the innovation implementation in the simulated network. Appendix C shows the variability of innovation implementation achieved with the diverse decision-making processes. As observed in the research project presented in Chapter 4, the theories dominated by mostly competence (i.e., Homo Economicus and Bounded Rationality) show less stochasticity in the diverse scenarios, which highlights the impact of communication and trust in the development of collective action. In theories where communication is a determinant parameter (Theory of Planned Behavior, Habitual Learning, and Descriptive Norm) the sustainable scenarios (Water supply reformation and Agricultural reformation) show variability in the innovation process, especially on years with higher water scarcity and higher rates of saltwater intrusion (i.e., last 30 years of the simulation). Due to the high variability and

randomness of the decision-making process in the Prospect Theory, high stochasticity of the results is observed. The climate variability showed to have less impact on the innovation implementation in the Descriptive Norm and Prospect Theory, especially in the Agricultural Reformation scenario.

5.4 Summary

The development of ABMs by creating software agents to play the role of irrigation users and modeling their interactions with the hydrological cycle is still in development but promises a better understanding of irrigation systems as anthropogenic landscapes. Two frameworks DInKa and SAHIO were developed to simulate the innovation process of new irrigation strategies like deficit irrigation where irrigation has been already applied. These robust frameworks show a transdisciplinary approach where participation from stakeholders is enhanced and used for sensitivity analysis and predictions.

In the first framework DInKa, centralized management was compared to a decentralized one and observed the aggregated outcome regarding the development of collective action. In the second framework SAHIO evaluated diverse decision-making processes and produce a sensitivity analysis of innovation implementation, groundwater extraction, and salt-water intrusion which could lead to optimal irrigation management policies. These robust frameworks are the first step towards a unified modeling of A-S-H systems using the complex network approach. By evaluating how heterogeneity characteristics influence the motivations for farmers to engage in conservation efforts, a deeper understanding is generated of the conditions under which groundwater conservation is likely to be successful.

Chapter 6

CONCLUSIONS AND OUTLOOK

Innovation

Behavior

Management

Economy

Collaboration

Policy

A-S-H
Networks

Education

Production

Climate

Irrigation

Resources

Soil

6 Conclusions and Outlook

Sustainability is measured as the weighted combination of reliability, resilience, and vulnerability measures [156]. This three-part research focused on the understanding of the diversity of this combination and was motivated by the following question raised by Di Baldassarre et al [54] "Should hydrologists be trying to predict human behavior?". In the past, some prominent hydrologists have resisted to any inclusion of complex economic or social components linked to hydrologic processes. They were critical of any models you could not calibrate and verify. Nevertheless, the predictions of traditional hydrological models have shown to be faulty. This highlights the need for more research on complex A-S-H processes and urges the collaboration with professionals from other disciplines and stakeholders in a transdisciplinary effort to better understand the social, economic, and physical impacts of the future water management challenges.

Simulation and participatory models are important tools for studying how resilience may emerge from interactions within a complex A-S-H network. Learning by experimentation and collective action was one of the focuses of the presented frameworks to understand the interactions between diverse components of the A-S-H networks. The frameworks attempted to combine realistic agent learning algorithms, process-based biophysical modules, and empirically parameterized decision-making processes. The overall research provides scientific insights to inform IWRM by detecting and understanding the relations between physical and social processes in an A-S-H network and the impact of water scarcity on these processes. With each project, the initial research questions were answered:

1. *How will water scarcity impact agricultural production and what are the optimal irrigation adaptation strategies?*

In the first project (Chapter 3), the climate variability in the Corn Belt was evaluated to find the optimal irrigation scheduling strategies focusing on deficit irrigation for possible future changes. We found that the Corn Belt, previously known for its fertile soil and ideal climate, is experiencing climate variations with longer periods of droughts and more high precipitation events. Therefore, irrigation is becoming a possible solution. Two optimizers for deficit irrigation showed positive water savings and increases in yield in the predicted water scarcity scenarios.

2. *How to collect data regarding the socio-hydrological dynamics in agriculture?*

In the second project (Chapter 4), a serious board game was developed and implemented to simulate the complex nonlinear response of irrigation strategies to climate and groundwater variability. The data collected gave us a better understanding of the communication, competence, and trust processes that generate collective action. The most important outcome of the game sessions was that the common economic-based behavior theories used to represent human decision-making show a narrow and erroneous representation, highlighting the need for more collaboration with social sciences to close this knowledge gap.

3. *How to simulate agro-socio-hydrological networks to optimize agricultural water management and evaluate policies impact?*

In the third project (Chapter 5), two frameworks were developed and tested based on innovation theories applied to an A-S-H network. In the first framework DInKa, centralized and decentralized

management strategies were compared and the aggregated outcome was observed regarding the development of collective action. In the second framework SAHIO, diverse decision-making processes were evaluated to produce a sensitivity analysis of innovation implementation, groundwater extraction, and salt-water intrusion to optimal irrigation management policies. Both frameworks implemented theories from different disciplines in a robust and efficient platform, where most of the feedback loops between human-water systems are taken into account. While both applications are theoretical examples, they give a glimpse of the multiple possibilities of knowledge integration using object programming.

6.1 Limitations

The main challenge of the presented methodologies remains the validation and the analysis of uncertainty which hinders the link of the simulated optimization with real-life practices and the reproduction of these methodologies beyond its initial objective. Each project had the following particular limitations:

- In the first project (Chapter 3): The user of the optimal irrigation strategies evaluated were considered to be homogeneous and static. The social characteristics of these users were assumed to be mainly through economic impacts. Nevertheless, these simulations help us understand the dynamics between historic and predicted climate and irrigation strategies.
- In the second project (Chapter 4): The game simplifies the hydrological process to enhance the social and (theoretical) economic processes that shape the collective action. This leads to equifinality and multi-finality which is difficult to separate from the outcomes of the game sessions. The evaluation of collaborative games is not standardized yet. All the case studies have very different debriefing methods to assess their effectiveness. Collaborations are tricky because of the conceptual bias in the disciplines and teaching techniques.
- In the third project (Chapter 5): While the use of diverse social theories in ABMs is increasing in literature, this is the first attempted to couple hydrological, agricultural, and economic models with innovation and diffusion theories. Therefore, the presented frameworks are still preliminary due to the model uncertainty and aggregated bias.
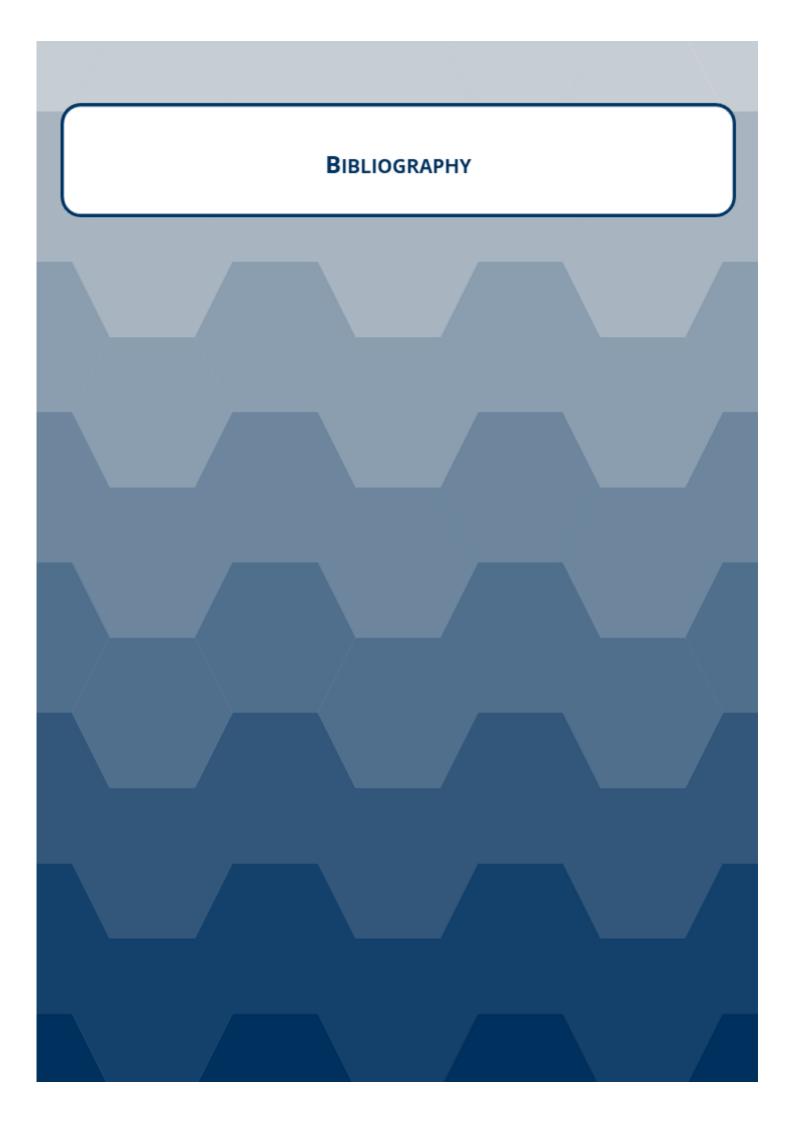
6.2 Outlook

Collaborative science involves participatory methods that aim to include, consult, and empower stakeholders to decrease the gap between researchers, policymakers, and resource users. While there is a general agreement that collaborative science or co-production of knowledge is an important skill and required for the evolution of science, there is less agreement on how to build an assessment to measure it, especially at scale and as a standardized approach. Collaborative approaches, especially serious games as shown in have a range of benefits, including the development of general communication abilities, empathy, social skills, and better solutions through teamwork. For each specific project presented in this study, this future work is recommended:

- For the first project (Chapter 3): The regionalization of areas surrounding the studied sites based on the optimal irrigation strategy with specialized soil and climate data.
- For the second project (Chapter 4): MAHIZ's can be adapted for place-based studies to explore the decision-making process with local stakeholders to find relevant decision-making processes and parameters in agrohydrological systems.
- For the third project (Chapter 5): Combination of theories to better represent deliberate decision-making and innovation diffusion.

Inter- and Trans-disciplinary simulations of interactions between human agency and water systems will increase the understanding of irrigation systems as anthropogenic landscapes in socioeconomic and environmental contexts. The reliability of these simulations is an important factor in identifying irrigation strategies and to improve agricultural water productivity. Nevertheless, theoretical implementations are an important element of generating relevant and reliable information to further synthesize knowledge effectively and applying it appropriately.

This research advocate wider adoption of collaborative methods, both qualitative and quantitative, as well as integrating explicit data and real-time decisions from stakeholders. Doing so will further the understanding of coupled natural and human systems in general, and specifically, help address social conflicts that may arise with the increasing environmental changes.

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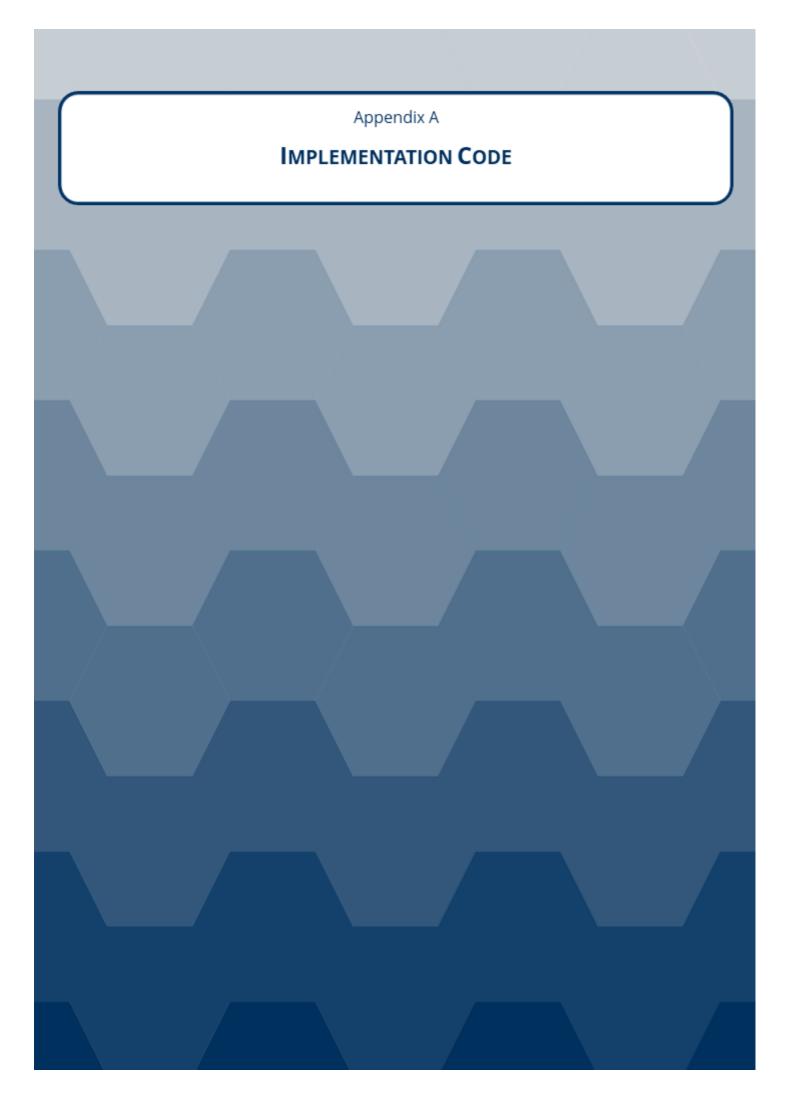
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Appendix A

IMPLEMENTATION CODE

Appendix A. Implementation Code

A.1 DInKA

```
model DInKa

/*Global */
global schedules: farm + shuffle(farmer) {

int no_farms <- 100;
float farm_density <- 0.005;
int neighborhood_distance <-300;
int no_friends <- 2;
int collective_distance <- 200;
int year_innovation <- 5;
int c_costs <- 300;
float Ii <- 1.5;
int Ic <- 70;
float so_b;
float happy_im <- 0.5;
int happy_farmers <- 0;
float N_trust <- 0.7;
float F_trust <- 0.9;
float C_trust <- 1;
float trust_in_collective <- 0.5;
float trans <- 0.2;
string scenario <- "s1";
int pic_size <- 80 parameter: true ;
list<float> mean_Yt;
list<float> mean_Op;
list<float> mean_Po;
list<float> mean_AI;
list<float> mean_B;
bool display_trust <- false parameter: true ;
bool display_neighborhood <- false parameter: true ;
bool display_friendship <- false parameter: true ;
bool display_collective <- false parameter: true ;
bool display_icons <- true  parameter: true ;
bool display_farm <- true  parameter: true ;
image_file background <-
image_file("../includes/farm_background.jpg");
geometry shape <-square
((1/farm_density)*no_farms^(1/2));
geometry free_space;
file crop_file <- csv_file("../includes/data.csv", ",", true );
matrix data<- matrix(crop_file);

/*Global - init */
init {
if scenario = "s1" {
farm_density <- 0.003;
no_friends <- 2;
collective_distance <-300;
Ii<-1.5;
trust_in_collective <-0.3;
} else {
farm_density <- 0.005;
no_friends <- 5;
collective_distance <-100;
Ii<-2.0;
trust_in_collective<-0.8;}
free_space <- copy(shape) - 100;

create farm number:no_farms {
location <- any_location_in(free_space);
free_space <- free_space - (shape + 100);}
ask farm {
neighborhood <- farm
at_distance(neighborhood_distance);
create farmer {
my_farm <- myself;
myself.my_farmer <- self;
location <- myself.location;}}
ask farmer {
friendship <- rnd(0, no_friends) among (farmer - self);
neighborhood <-  (my_farm.neighborhood collect
each.my_farmer); }
ask one_of(farm){
my_farmer.in_collective <- true ;
ask farm at_distance(collective_distance){
my_farmer.in_collective <- true ;}}
ask farmer where(each.in_collective){
collective <- farmer where (each.in_collective) - self;}
ask farmer{
do initialize_trust;}}

/*Global - reflex */
reflex initial_status when: cycle < year_innovation{
ask (farmer){
innovation_status <- "closed";}}
reflex innovation_trigger when: cycle =
year_innovation{
ask 3 among (farmer where each.in_collective){
innovation_status <- "Implementation";
year_implementation <- cycle;}}
reflex innovation_update when: cycle >=
year_innovation{
ask (farmer){
if length(trust_values.keys) = 0{
innovation_status <- "closed";
}else{
if innovation_status = "Implementation" or
innovation_status = "promotion"{
loop linked_farmer over: trust_values.keys {
if linked_farmer.innovation_status = "closed"{
linked_farmer.innovation_status <- "reception";}}}}}
reflex update_variable when: cycle >= year_innovation{
so_b <- (count(farmer, each.innovation_status =
"Implementation")/length(farmer));}
reflex benefit_update {
ask farm{
if my_farmer.innovation_status = "closed" or
my_farmer.innovation_status = "reception"{
do initial_calculations;}
if my_farmer.innovation_status = "Implementation" or
my_farmer.innovation_status = "promotion"{
do new_calculations;}
mean_Yt <+ (farm mean_of last(each.Yt));
mean_Op <+ (farm mean_of last(each.Op));
mean_Po <+ (farm mean_of last(each.Po));
mean_AI <+ (farm mean_of last(each.AI)); }
ask farmer {
```

```
if innovation_status = "closed" or innovation_status =
"reception"{
do initial_benefits_calculation;}
if innovation_status = "Implementation" or
innovation_status = "promotion"{
do new_benefit_calculation;}
mean_B <+ (farmer mean_of last(each.B));}}
reflex save_results {
save [scenario,cycle,(farmer count
(each.innovation_status = "Implementation")),
(farmer count (each.innovation_status = "promotion"))]
to: "test.csv" type:csv rewrite: false;}
reflex stop_simulation when: cycle = 29 {
do pause;}}

/*Farm*/
species farm frequency: 0 {
farmer my_farmer;
list<float> Yt;
list<float> Op;
list<float> Po;
list<float> AI;
list<farm> neighborhood;
float farm_area;
geometry shape <- circle(rnd(25, 50));
aspect default{
if display_farm{
draw shape color: #white;
}else {
draw shape color: #green;}}
action initial_calculations{
farm_area <- shape.area*0.0001;
Yt <- Yt + [farm_area*float(data[3,cycle])];
Op <- Op + [farm_area*c_costs];
Po <- Po + [Yt[cycle]*(float(data[4,cycle]))-Op[cycle]];
AI <- AI + [(float(data[2,cycle]))/(float(data[1,cycle]))];
}
action new_calculations {
farm_area <- shape.area*0.0001;
Yt <- Yt + [(farm_area*float(data[3,cycle]))*Ii];
Op <- Op + [(farm_area*c_costs) + Ic];
Po <- Po + [Yt[cycle]*(float(data[4,cycle]))-Op[cycle]];
AI <- AI + [(float(data[2,cycle]))/(float(data[1,cycle]))];}}

/*Farmer*/
species farmer frequency: 0{
farm my_farm;
list<farmer> friendship;
list<farmer> collective;
list<farmer> neighborhood;
bool in_collective <- false;
bool happy <- false;
list<float> B;
int year_implementation;
rgb color <- #black;
string innovation_status <- "closed" among:
["closed","reception", "Implementation", "promotion"];
image_file icon_closed <-
image_file("../includes/closed.png");
image_file icon_happy <-
image_file("../includes/happy.png");
image_file icon_implementation <-
image_file("../includes/implementation.png");
```

```
image_file icon_promotion <-
image_file("../includes/promotion.png");
image_file icon_reception <-
image_file("../includes/reception.png");
aspect default {
if display_icons {
if innovation_status = "closed" {
draw icon_closed size:pic_size;}
if innovation_status = "reception" {
draw icon_reception size:pic_size;}
if innovation_status = "Implementation" {
draw icon_implementation size:pic_size;}
if innovation_status = "promotion" {
if happy {
draw icon_happy size:pic_size;
}else {
draw icon_promotion size:pic_size;}}
} else {
draw circle(7) color: color;}}
map<farmer,float> trust_values;
action initialize_trust {
if in_collective{
loop i over: remove_duplicates(neighborhood +
friendship + collective) {
float initial_value <- 0.0;
if i in neighborhood{
initial_value <- N_trust;}
if i in friendship {
initial_value <- F_trust;}
if i in collective {
initial_value <- C_trust;}
trust_values[i] <- initial_value; }
} else {
loop i over: remove_duplicates(neighborhood +
friendship + collective) {
float initial_value <- 0.0;
if i in neighborhood{
initial_value <- N_trust;}
if i in friendship {
initial_value <- F_trust;}
if i.in_collective {
initial_value <- initial_value*trust_in_collective;}
trust_values[i] <- initial_value; }}}
aspect links {
if (display_trust) {
loop far over: remove_duplicates(friendship + collective
+ neighborhood) {
draw line ([location, far.location]) +
1.5*(trust_values[far]) color: #black;}}
if (display_neighborhood) {
loop far over: neighborhood {
draw line ([location, far.location]) color: #red border:
#black size:200;}}
if (display_friendship) {
loop far over: friendship {
draw line ([location, far.location]) color: #blue border:
#black size:200; }}
if (display_collective) {
loop far over: collective {
draw line ([location, far.location]) color: #orange
border: #black size:200;}}}

/*Innovation stage: Closed */
action initial_benefits_calculation {
```

```
B <- B + (my_farm.Po[cycle]/my_farm.Op[cycle]) +
(my_farm.AI[cycle]);}

/*Innovation stage: Implementation */
action new_benefit_calculation {
B <- B + [so_b + (my_farm.Po[cycle]/my_farm.Op[cycle])
+ (my_farm.AI[cycle])];}

/*Innovation stage: Reception */
reflex reception when:(innovation_status =
"reception"){
float R;
int counter <- 0;
float happy_coeff;
loop linked_farmer over: trust_values.keys{
if linked_farmer.happy{
happy_coeff <-1 + happy_im;
}else {
happy_coeff <- 1;}
R <- R +
linked_farmer.B[cycle]*(trust_values[linked_farmer]*ha
ppy_coeff);
counter <- counter + 1;}
R <- R / counter;
if B[cycle] < R {
innovation_status <- "Implementation";
year_implementation <- cycle;}}

/*Innovation stage: Promotion */
reflex promotion when:(innovation_status =
"Implementation" and cycle > year_implementation){
float P;
int counter <- 0;
loop linked_farmer over: trust_values.keys{
P <- P +
linked_farmer.B[cycle]*trust_values[linked_farmer];
counter <- counter + 1;}
P <- P / counter;
if B[cycle] > P {
innovation_status <- "promotion";}}

reflex happy when:(innovation_status = "promotion"){
float av_5year <- mean(5 last B);
if av_5year < B[cycle]{
happy <- true ;
happy_farmers <- happy_farmers + 1;}
else {
happy <- false;}}}
experiment DInKa_batch type: batch repeat:4
keep_seed: true  until: cycle > 29 parallel: false{
parameter "scenario" var: scenario  among: ["s1", 's2'];}
experiment DInKa type: gui keep_seed: true {
parameter "transparency" var: trans init:0.2;
parameter "scenario" var: scenario  among: ["s1", 's2'];
output {
display map autosave: true  synchronized: true {
image background transparency: trans;
species farm transparency: 0.4;
species farmer aspect: links;
species farmer;}
display "Environment Factors" type: java2D {

chart "Environmental Factors" type: series  title_font:
'SanSerif' title_font_size: 28.0 label_font: 'SanSerif'
label_font_size: 18 legend_font_style: 'plain'
legend_font: 'SanSerif'
legend_font_size: 18 x_label: "Years" x_serie_labels:
(1980+(cycle+1)) tick_font_size:15 y_label: "Yield [kg/ha]"
y2_label: "Aridity Index" y_tick_line_visible: false
x_tick_line_visible: false{
data "Yield [kg/ha]" value: mean_Yt marker_shape:
marker_circle color: #red;
data "Aridity Index [-]" value: mean_AI marker_shape:
marker_circle color: #blue use_second_y_axis: true ;}}
display "Economic Factors" type: java2D {
chart "Economic Factor" type: series title_font: 'SanSerif'
title_font_size: 28.0 label_font: 'SanSerif' label_font_size:
18 legend_font_style: 'plain' legend_font: 'SanSerif'
legend_font_size: 18 x_label: "Years" x_serie_labels:
(1980+(cycle+1)) tick_font_size:15 y_label: "$"
y_tick_line_visible: false x_tick_line_visible: false{
data "Profit [$]" value: mean_Po marker_shape:
marker_circle color: #red;
data "Operational costs [$]" value: mean_Op
marker_shape: marker_circle color: #blue;}}
display "Farmers Benefits" type: java2D {
chart "Farmers Benefits" type: series title_font:
'SanSerif' title_font_size: 28.0 label_font: 'SanSerif'
label_font_size: 18 legend_font_style: 'plain'
legend_font: 'SanSerif'
legend_font_size: 18 x_label: "Years" x_serie_labels:
(1980+(cycle+1)) tick_font_size:15 y_label: "Farmer
Benefits" y_tick_line_visible: false x_tick_line_visible:
false{
data "Benefit [-]" value: mean_B marker_shape:
marker_circle color: #blue;}}
display "Status of Farmers" type: java2D {
chart "Innovation Status of Farmers" type:histogram
style:stack title_font: 'SanSerif' title_font_size: 28.0
label_font: 'SanSerif' label_font_size: 18
legend_font_style: 'plain' legend_font: 'SanSerif'
legend_font_size: 18 x_label: "Years" x_serie_labels:
(1980+(cycle+1)) tick_font_size:12 y_label: "Number of
Farmers" y_tick_line_visible: false x_tick_line_visible:
false{
data "Farmers in Closed" value: length(farmer where
(each.innovation_status = "closed"))
accumulate_values: true  color: rgb (88, 88, 88,255);
data "Farmers in Reception" value: length(farmer
where (each.innovation_status = "reception"))
accumulate_values: true        color: rgb (63, 72,
204,255);
data "Farmers in Implementation" value: (farmer count
(each.innovation_status = "Implementation"))
accumulate_values: true  color: rgb (139, 56, 183,255);
data "Farmers in Promotion" value: (length(farmer
where (each.innovation_status = "promotion"))-
length(farmer where (each.happy = true )))
accumulate_values: true  color: rgb (149, 91, 58,255);
data "Happy Farmers" value: length(farmer where
(each.happy = true )) accumulate_values: true  color:
rgb (213, 25, 32,255);}}}}
```

A.2 SAHIO

```
model SAHI_O

/*GLOBAL*/
global schedules: farm + shuffle(farmer) {

// Data files
matrix data;
file ag_file <- csv_file("../includes/data_ag.csv", ",", true );
matrix data_ag<- matrix(ag_file);
file base_file <- csv_file("../includes/data_base.csv", ",",
true );
matrix data_base<- matrix(base_file);
file water_file <- csv_file("../includes/data_water.csv", ",",
true );
matrix data_water<- matrix(water_file);

// Farm parameters
int no_farms <- 50;
int neighborhood_distance <-0;

// Economical parameters
list<float> mean_Co;
list<float> mean_Po;

// Hydrological parameters
list<float> mean_Irr;
list<float> mean_GWL;
list<float> mean_SL;
list<float> mean_GWL_D_P;
list<float> mean_Sal_D_P;
list<float> mean_GWL_D_S;
list<float> mean_Sal_D_S;
list<float> mean_GWL_DR;
list<float> mean_Sal_DR;

// Farmer parameters
int no_friends <- 2;
int collective_distance <- 200;

// Social parameters
float social_pressure;
float external_social_pressure;
float internal_social_pressure;
float trust_in_collective <- 0.5;

// Satisfaction parameters
float happy_impact <- 0.7;
int happy_farmers <- 0;
list<float> mean_Be;

// Innovation parameters
int year_innovation <- 3;

// Policy scenarios
string Policy_Scenario <- "Baseline" among: ["Baseline",
"Water_Policy", "Agricultural_Policy"] parameter: true ;

// Behavior theories parameters
string Behavior_Theory <- "Homo_Economicus" among:
["Homo_Economicus", "Bounded_Rationality",
"Theory_Planned_Behavior", "Habitual_Learning",
```

```
"Descriptive_Norm", "Prospect_Theory"] parameter:
true ;
float N_trust <- 0.5;
float F_trust <- 0.7;
float C_trust <- 0.9;
float comm_eff <- 1;

// Display parameters
float transparency <- 0.0;
int pic_size <- 750;
bool Display_trust <- false;
bool Neighborhood_links <- false parameter: true ;
bool Friendship_links <- false parameter: true ;
bool Collective_links <- false parameter: true ;
bool Farmer_Icon <- true  parameter: true ;
bool Farm <- true ;
geometry shape <-square (10000);
geometry free_space;

/*GLOBAL-INITIALIZATION */
init {
// Policy scenarios
if Policy_Scenario = "Baseline"{
data<-data_base;}
if Policy_Scenario = "Water_Policy"{
data<-data_water;}
if Policy_Scenario = "Agricultural_Policy"{
data<-data_ag;}
// Behavior Theories
if Behavior_Theory = "Homo_Economicus" {
no_friends <- 20;
neighborhood_distance <-4000;
collective_distance <-8000;
trust_in_collective <-0.0;
N_trust <- 0.0;
F_trust <- 0.0;
C_trust <- 0.0;
comm_eff <- 1.0;
do action: MoHuB1}
if Behavior_Theory = "Bounded_Rationality" {
no_friends <- 10;
neighborhood_distance <-2000;
collective_distance <-3200;
trust_in_collective <-0.5;
N_trust <- rnd(0.25,0.5);
F_trust <- rnd(0.25,0.5);
C_trust <- rnd(0.25,0.5);
comm_eff <- rnd(0.7,0.9);
 do action: MoHuB2}
if Behavior_Theory = "Theory_Planned_Behavior" {
no_friends <- 7;
neighborhood_distance <-800;
collective_distance <-1600;
trust_in_collective <-0.5;
N_trust <- rnd(0.5,0.7);
F_trust <- rnd(0.5,0.7);
C_trust <- rnd(0.7,0.9);
comm_eff <- rnd(0.5,0.7);
do action: MoHuB3}
if Behavior_Theory = "Habitual_Learning" {
no_friends <- 7;
```

```
neighborhood_distance <-800;
collective_distance <-1600;
trust_in_collective <-0.5;
N_trust <- 0.5;
F_trust <- 0.7;
C_trust <- 0.9;
comm_eff <- rnd(0.7,0.8);
do action: MoHuB4}
if Behavior_Theory = "Descriptive_Norm" {
no_friends <- 7;
neighborhood_distance <-800;
collective_distance <-1600;
trust_in_collective <-1.0;
N_trust <- 1.0;
F_trust <- 1.0;
C_trust <- 1.0;
comm_eff <- 1;
do action: MoHuB5}
if Behavior_Theory = "Prospect_Theory" {
no_friends <- 3;
neighborhood_distance <-700;
collective_distance <-1000;
trust_in_collective <-0.7;
N_trust <- rnd(0.3,0.5);
F_trust <- rnd(0.5,0.7);
C_trust <- rnd(0.7,0.9);
comm_eff <- rnd(0.5,0.6);
do action: MoHuB6}

// Farm and farmer creation
free_space <- copy(shape)-400;
create farm number:no_farms {
location <- any_location_in(free_space);
free_space <- free_space - (shape + 500);}
ask farm {
neighborhood <- farm
at_distance(neighborhood_distance);
create farmer {
my_farm <- myself;
myself.my_farmer <- self;
location <- myself.location;}}

// Network creation
ask farmer {
friendship <- rnd(0, no_friends) among (farmer - self);
neighborhood <- (my_farm.neighborhood collect
each.my_farmer); }
ask one_of(farm) {
my_farmer.in_collective <- true ;
ask farm at_distance(collective_distance) {
my_farmer.in_collective <- true ;}}
ask farmer where(each.in_collective){
collective <- farmer where (each.in_collective) - self;}
ask farmer{
do initialize_trust;}}

/*GLOBAL-REFLEX */

/* Innovation status: Closed */
reflex initial_innovation_status when: cycle <
year_innovation{
ask (farmer){
innovation_status <- "Learning";}}
```

```
/* Innovation status: Initial Implementation */
reflex innovation_trigger when: cycle =
year_innovation{
ask 1 among (farmer where each.in_collective){
initial_innovation_farmer_collective <- false;
innovation_status <- "Implementation";
year_implementation <- cycle;}
ask 2 among (farmer where
each.initial_innovation_farmer_collective){
innovation_status <- "Implementation";
year_implementation <- cycle;}}

/* Innovation diffusion */
reflex innovation_diffusion when: cycle >=
year_innovation{
ask (farmer){
if length(trust_values.keys) = 0{
innovation_status <- "Learning";
}else{
if innovation_status = "Implementation" or
innovation_status = "promotion"{
loop linked_farmer over: trust_values.keys {
if linked_farmer.innovation_status = "Learning"{
linked_farmer.innovation_status <- "Receiving";}}}}}}
/* Social pressure estimation */
reflex initial_social_pressure when: cycle >=
year_innovation{
external_social_pressure <- (count(farmer,
each.innovation_status =
"Implementation")/length(farmer));
ask (farmer){
if length(trust_values.keys) = 0{
internal_social_pressure <- 0.0;
}else{
loop linked_farmer over: trust_values.keys {
if linked_farmer.innovation_status = "Implementation"
or innovation_status = "promotion"{
internal_social_pressure <- ((count(farmer,
each.innovation_status = "promotion") + count(farmer,
each.happy = true ))/length(linked_farmer));}}}}
social_pressure <- external_social_pressure
+internal_social_pressure;}

/* Benefit analysis */
reflex benefit_calculations {
ask farm{
if my_farmer.innovation_status = "Learning" or
my_farmer.innovation_status = "Receiving"{
do initial_farm_calculations;}
if my_farmer.innovation_status = "Implementation" or
my_farmer.innovation_status = "promotion"{
do new_farm_calculations;}
mean_Co <+ (farm mean_of last(each.Co)/4);
mean_Po <+ (farm mean_of last(each.Po)/4);
mean_Irr <+ (farm mean_of last (each.Irr)/4);
mean_GWL <+ (farm mean_of last (each.GWL)/4);
mean_SL <+ (farm mean_of last (each.SL)/4);
mean_GWL_D_P <+ (farm mean_of last
(each.GWL_D_P));
mean_Sal_D_P <+ (farm mean_of last (each.Sal_D_P));
mean_GWL_D_S <+ (farm mean_of last
(each.GWL_D_S));
mean_Sal_D_S <+ (farm mean_of last (each.Sal_D_S));
mean_GWL_DR <+ (farm mean_of last (each.GWL_DR));
```

```
mean_Sal_DR <+ (farm mean_of last (each.Sal_DR));}
ask farmer {
if innovation_status = "Learning" or innovation_status =
"Receiving"{
do initial_farmer_calculation;}
if innovation_status = "Implementation" or
innovation_status = "promotion"{
do new_farmer_calculation;}
mean_Be <+ (farmer mean_of last(each.Be));}}

/* End simulation */
reflex stop_simulation when: cycle = 20 {
do pause;}}

/*GRID */
grid plot height: 8 width: 1{
rgb color <- #khaki;}

/*FARM*/
species farm frequency: 0 {
farmer my_farmer;
plot my_plot;
list<float> Co;
list<float> Po;
list<float> Irr;
list<float> GWL;
list<float> SL;
list<float> GWL_D_P;
list<float> Sal_D_P;
list<float> GWL_D_S;
list<float> Sal_D_S;
list<float> GWL_DR;
list<float> Sal_DR;
list<farm> neighborhood;
float farm_area;
geometry shape <- square(rnd(200, 500));
aspect default {
if Farm{
draw shape color: #green;
}else {
draw shape color: #white;}}
action initial_farm_calculations{
farm_area <- (shape.area);
GWL <- GWL +
[(farm_area*(float(data[5,cycle])))/30000];
SL <- SL + [(farm_area*(float(data[6,cycle])))/30000];
Irr <- Irr + [(farm_area*(float(data[7,cycle])))/30000];
Po <- Po + [(farm_area*(float(data[8,cycle])))/30000];
Co <- Co + [(farm_area*(float(data[9,cycle])))/30000];
GWL_DR <- GWL_DR + [(float(data[10,cycle]))];
GWL_D_S <- GWL_D_P + [(float(data[11,cycle]))];
GWL_D_P <- GWL_D_P + [(float(data[12,cycle]))];
Sal_DR <- Sal_DR + [(float(data[13,cycle]))];
Sal_D_S <- Sal_D_S + [(float(data[14,cycle]))];
Sal_D_P <- Sal_D_P + [(float(data[15,cycle]))];}
action new_farm_calculations {
farm_area <- (shape.area);
GWL <- GWL +
[(farm_area*(float(data[0,cycle])))/30000];
SL <- SL + [(farm_area*(float(data[1,cycle])))/30000];
Irr <- Irr + [(farm_area*(float(data[2,cycle])))/30000];
Po <- Po + [(farm_area*(float(data[3,cycle])))/30000];
Co <- Co + [(farm_area*(float(data[4,cycle])))/30000];
GWL_DR <- GWL_DR + [(float(data[10,cycle]))];
```

```
GWL_D_S <- GWL_D_P + [(float(data[11,cycle]))];
GWL_D_P <- GWL_D_P + [(float(data[12,cycle]))];
Sal_DR <- Sal_DR + [(float(data[13,cycle]))];
Sal_D_S <- Sal_D_S + [(float(data[14,cycle]))];
Sal_D_P <- Sal_D_P + [(float(data[15,cycle]))];}}

/*Farmer*/
species farmer frequency: 0 {
farm my_farm;
plot my_plot;
list<farmer> friendship;
list<farmer> collective;
list<farmer> neighborhood;
list<float> Be;
bool in_collective <- false;
bool initial_innovation_farmer_collective <- true ;
bool happy <- false;
int year_implementation;
string innovation_status <- "Learning" among:
["Learning","Receiving", "Implementation",
"promotion"];
image_file icon_closed <-
image_file("../includes/closed.png");
image_file icon_happy <-
image_file("../includes/happy.png");
image_file icon_implementation <-
image_file("../includes/implementation.png");
image_file icon_promotion <-
image_file("../includes/promotion.png");
image_file icon_reception <-
image_file("../includes/reception.png");
aspect default {
if Farmer_Icon {
if innovation_status = "Learning" {
draw icon_closed size:pic_size;}
if innovation_status = "Receiving" {
draw icon_reception size:pic_size;}
if innovation_status = "Implementation" {
draw icon_implementation size:pic_size;}
if innovation_status = "promotion" {
if happy {
draw icon_happy size:pic_size;
}else {
draw icon_promotion size:pic_size;}}} else {
draw circle(5) color: #black;}}
map<farmer,float> trust_values;
action initialize_trust {
if in_collective{
loop i over: remove_duplicates(neighborhood +
friendship + collective) {
float initial_value <- 0.0;
if i in neighborhood{
initial_value <- N_trust;}
if i in friendship {
initial_value <- F_trust;}
if i in collective {
initial_value <- C_trust;}
trust_values[i] <- initial_value; }
} else {
loop i over: remove_duplicates(neighborhood +
friendship + collective) {
float initial_value <- 0.0;
if i in neighborhood{
initial_value <- N_trust;}
```

```
if i in friendship {
initial_value <- F_trust;}
if i.in_collective {
initial_value <- C_trust*trust_in_collective;}
trust_values[i] <- initial_value; }}}
aspect links {
if (Display_trust) {
loop all_farmers over: remove_duplicates(friendship +
collective + neighborhood) {
draw line ([location, all_farmers.location]) +
1.5*(trust_values[all_farmers]) color: #black;}}
if (Neighborhood_links) {
loop all_farmers over: neighborhood {
draw line ([location, all_farmers.location]) color: #red;}}
if (Friendship_links) {
loop all_farmers over: friendship {
draw line ([location, all_farmers.location]) color: #blue;
}}
if (Collective_links) {
loop all_farmers over: collective {
draw line ([location, all_farmers.location]) color:
#purple;}}}

/*Innovation stage: Learning */
action initial_farmer_calculation {
Be <- Be + (my_farm.Co[cycle]/(my_farm.Po[cycle]*10))
+ (my_farm.SL[cycle]/my_farm.GWL[cycle]);}

/*Innovation stage: Implementation */
action new_farmer_calculation {
Be <- Be + [social_pressure +
(my_farm.Co[cycle]/(my_farm.Po[cycle]*10)) +
(my_farm.SL[cycle]/my_farm.GWL[cycle])];}

/*Innovation stage: Receiving */
reflex reception when:(innovation_status =
"Receiving"){
float R;
int counter <- 0;
float happy_coeff;
loop linked_farmer over: trust_values.keys{
if linked_farmer.happy{
happy_coeff <- 1 + happy_impact;
}else {
happy_coeff <- 1;}
R <- R +
((linked_farmer.Be[cycle]*trust_values[linked_farmer]))
*happy_coeff*comm_eff;
counter <- counter + 1;}
if counter = 0 {
R <- 0;
}else {
R <- R / counter;}
if Be[cycle] < R {
innovation_status <- "Implementation";
year_implementation <- cycle;}}
/*Innovation stage: Promotion */
reflex promotion when:(innovation_status =
"Implementation" and cycle > year_implementation){
float P;
int counter <- 0;
loop linked_farmer over: trust_values.keys{

P <- P +
(linked_farmer.Be[cycle]*trust_values[linked_farmer])*
comm_eff;
counter <- counter + 1;}
if counter = 0 {
P <- 0;
}else {
P <- P / counter;}
if Be[cycle] > P {
innovation_status <- "promotion";}}
reflex happy when:(innovation_status = "promotion"){
float average <- mean(3 last Be);
if average < Be[cycle]{
happy <- true ;
happy_farmers <- happy_farmers + 1;}
else {
happy <- false;
innovation_status <- "Receiving";}}}
experiment SAHI_O  type: gui keep_seed: true  {
float minimum_cycle_duration <- 0.4;

reflex results {
ask simulations{
save [cycle, (farm mean_of last (each.Po))] to:
"Po_results_" + Policy_Scenario + "_" + Behavior_Theory
+ ".csv" type: csv rewrite: false;
save [cycle, (farm mean_of last (each.GWL_DR)), (farm
mean_of last (each.GWL_D_P)), (farm mean_of
last(each.GWL_D_S))] to: "GW_D_results_" +
Policy_Scenario + "_" + Behavior_Theory + ".csv" type:
csv rewrite: false;
save [cycle, (farm mean_of last (each.Sal_DR)), (farm
mean_of last (each.Sal_D_P)), (farm mean_of
last(each.Sal_D_S))] to: "Sal_D_results_" +
Policy_Scenario + "_" + Behavior_Theory + ".csv" type:
csv rewrite: false;
save [cycle,(farmer count (each.innovation_status =
"Learning")),(farmer count (each.innovation_status =
"Receiving")),(farmer count (each.innovation_status =
"Implementation")),(farmer count
(each.innovation_status = "promotion")),(farmer count
(each.happy = true ))] to: "farmer_results_" +
Policy_Scenario + "_" + Behavior_Theory + ".csv" type:
csv rewrite: false;}}
output {
layout
horizontal([vertical([0::6571,1::3429])::5019,vertical([2::6
488,3::3512])::4981) tabs:false toolbars:false editors:
false parameters:true  consoles:false navigator:false
tray:false;
display map {
grid plot lines: #darkkhaki;
species farm transparency: 0.4;
species farmer aspect: links;
species farmer;}
display "Results over distance" type: java2D {
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0}type: series
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title_font_size: 13.0
label_font: 'SanSerif'
label_font_size: 10
legend_font_style: 'plain'
legend_font: 'SanSerif'
```

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tick_font_size: 10
y_label: "Groundwater Level [m]"
y_tick_line_visible: false
x_tick_line_visible: false{
data "Reference [m]" value: mean_GWL_DR
marker_shape: marker_empty style: spline color: #red;
data "Profitable solution [m]" value: mean_GWL_D_P
marker_shape: marker_empty style: spline color: #blue;
data "Sustainable solution [m]" value: mean_GWL_D_S
marker_shape: marker_empty style: spline color:
#green;}
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label_font_size: 10
legend_font_style: 'plain'
legend_font: 'SanSerif'
legend_font_size: 10
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x_serie_labels: (2000+((cycle)*400))
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y_label: "Salinity [dS/m]"
y_tick_line_visible: false
x_tick_line_visible: false{
data "Reference [dS/m]" value: mean_Sal_DR
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data "Profitable solution [dS/m]" value: mean_Sal_D_P
marker_shape: marker_empty style: spline color: #blue;
data "Sustainable solution [dS/m]" value:
mean_Sal_D_S marker_shape: marker_empty style:
spline color: #green;}}
display "Results over time" type: java2D {
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0}type: series
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label_font_size: 10
legend_font_style: 'plain'
legend_font: 'SanSerif'
legend_font_size: 10
x_label: "Time steps [3 years]"
x_serie_labels: cycle
tick_font_size: 10
y_label: "Groundwater Level [m]"
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x_tick_line_visible: false{
data "Groundwater Level [m]" value: mean_GWL
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;}
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title_font_size: 13.0
label_font: 'SanSerif'
label_font_size: 10
legend_font_style: 'plain'

legend_font: 'SanSerif'
legend_font_size: 10
x_label: "Time steps [3 years]"
x_serie_labels: cycle
tick_font_size: 10
y_label: "Salinity [dS/m]"
y_tick_line_visible: false
x_tick_line_visible: false{
data "Salinity [dS/m]" value: mean_SL marker_shape:
marker_empty style: spline color: #red;}
chart "Profit" size: {1.0,0.25} position: {0, 0.5} type:
series
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x_tick_line_visible: false{
data "Profit 10^6 [$]" value: mean_Po marker_shape:
marker_empty style: spline color: #green;}
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type: series
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title_font_size: 13.0
label_font: 'SanSerif'
label_font_size: 10
legend_font_style: 'plain'
legend_font: 'SanSerif'
legend_font_size: 10
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x_tick_line_visible: false{
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display "Status of Farmers" type: java2D {
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label_font_size: 10
legend_font_style: 'plain'
legend_font: 'SanSerif'
legend_font_size: 10
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tick_font_size: 10
y_label: "Number of Farmers"
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```

```
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204,255);
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(each.innovation_status = "Implementation"))
accumulate_values: true  color: rgb (139, 56, 183,255);
data "promotion" value: (length(farmer where
(each.innovation_status = "promotion"))-length(farmer
where (each.happy = true ))) accumulate_values: true
color: rgb (149, 91, 58,255);
data "Satisfied" value: length(farmer where
(each.happy = true )) accumulate_values: true  color:
rgb (213, 25, 32,255);}}}}
```

Appendix B
SAHIO's Decision-Making Process for each MoHuB Theory

Appendix B. SAHIO's Decision-Making Process for Each MoHuB Theory
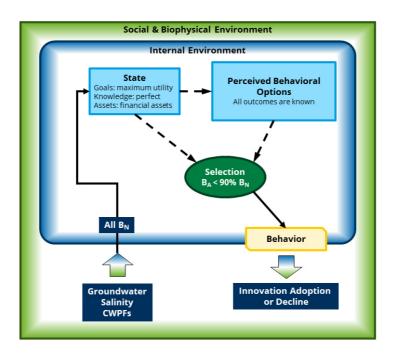
Figure B. 1: MoHuB for Homo Economicus Theory.
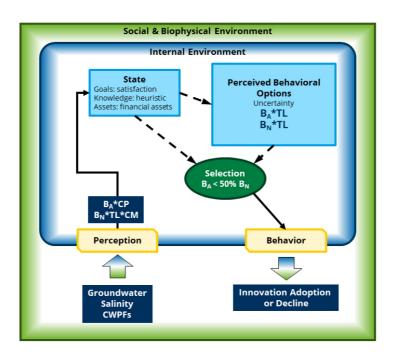
Figure B. 2: MoHuB for Bounded Rationality Theory.
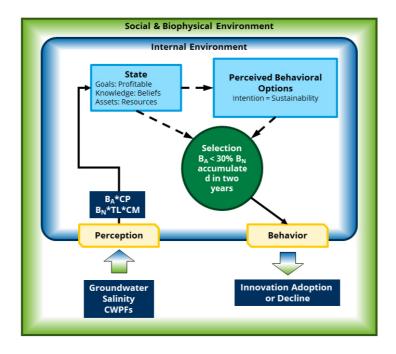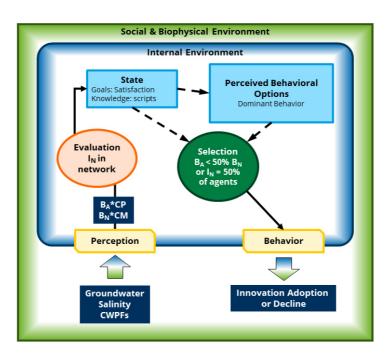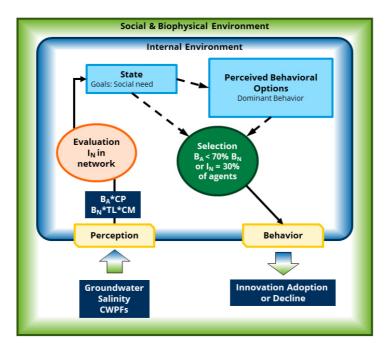
Figure B. 3: MoHuB for Theory of Planned Behavior.
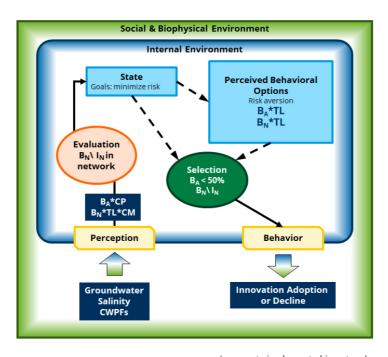
I_N = agents implemented in network

Figure B. 4: MoHuB for Habitual Learning Theory

I_N = agents implemented in network

Figure B. 5: MoHuB for Descriptive Norm Theory.
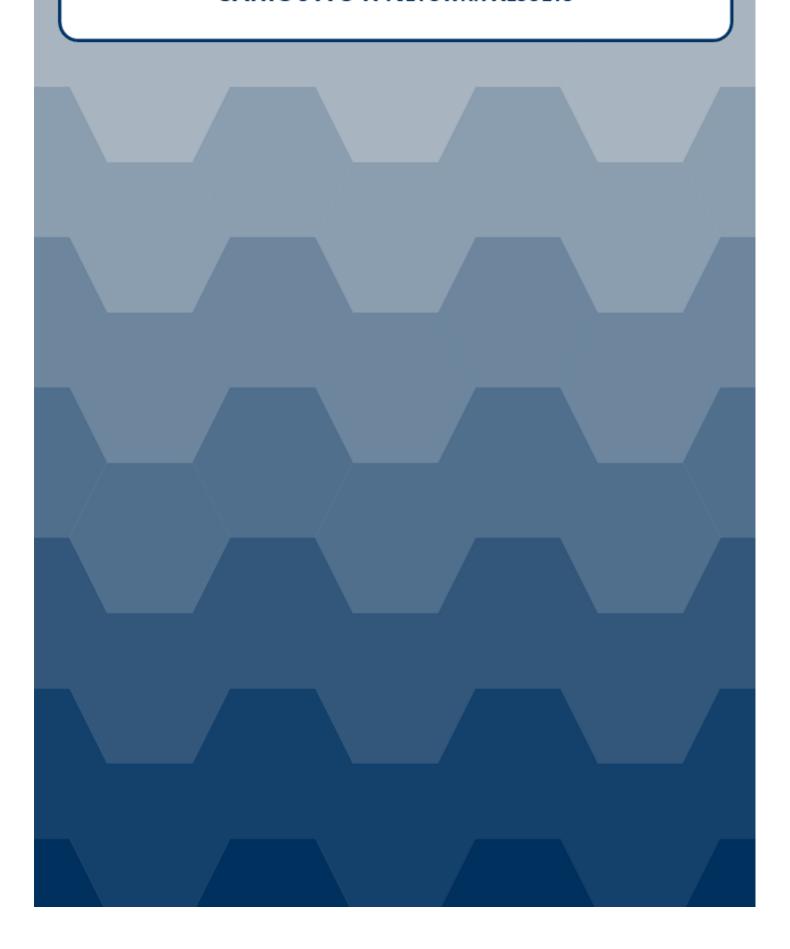
I_N = agents implemented in network

Figure B. 6: MoHuB for Prospect Theory

Appendix C

SAHIO's A-S-H Netowrk Results

Appendix C. SAHIO A-S-H Innovation Results
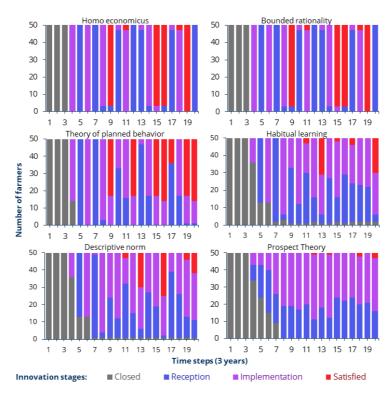
Figure C. 1: Results of Baseline Scenario.
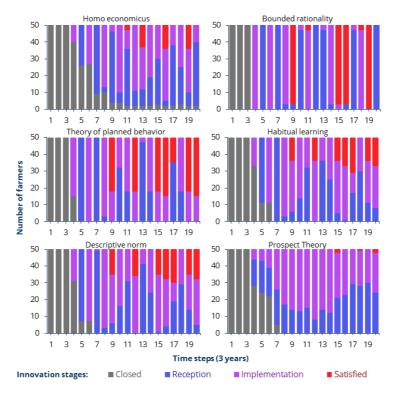
Figure C. 2: Results of Water Policy Scenario.
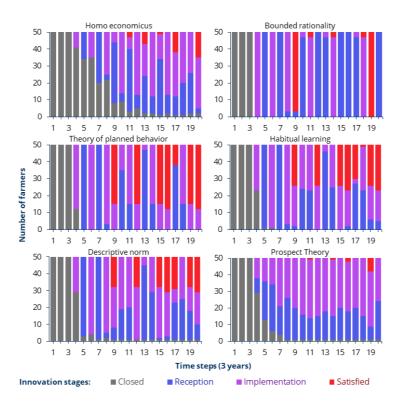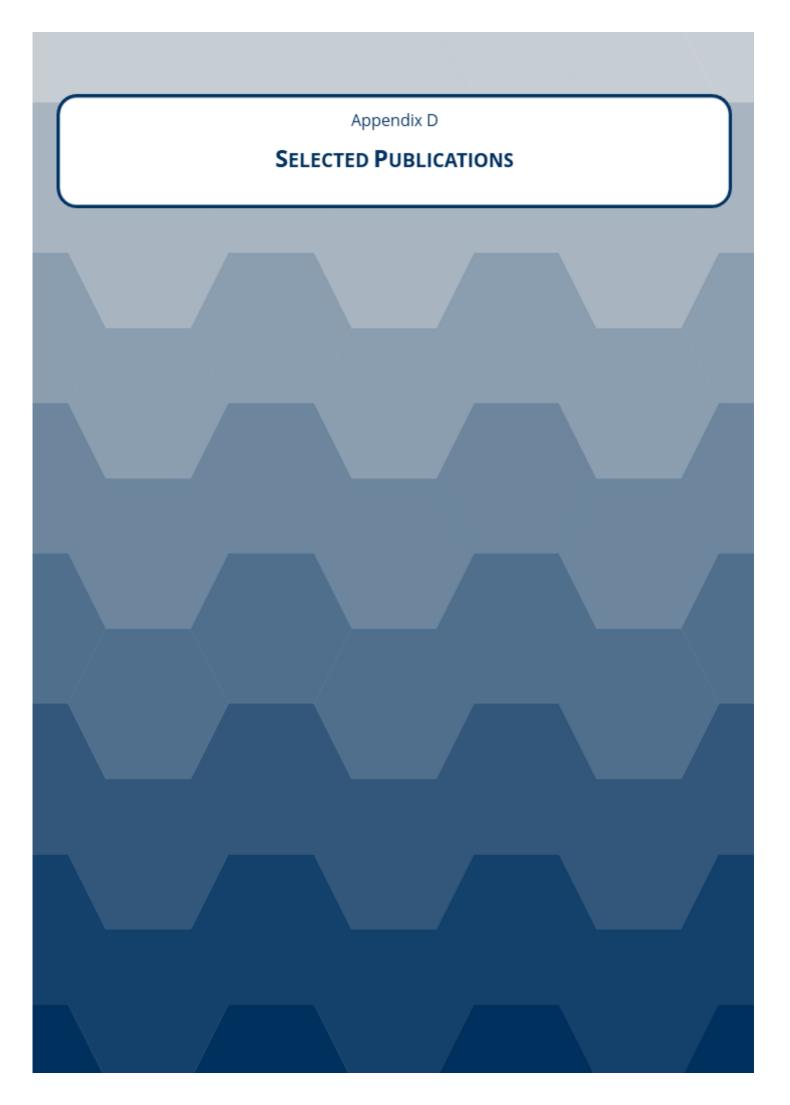
Figure C. 3: Results of Agricultural Policy Scenario.

Appendix D

SELECTED PUBLICATIONS

Appendix D. Selected Publications

- *Page 103*

Orduña Alegría, M. E.; Schütze, N.; Niyogi, D.

Evaluation of Hydroclimatic Variability and Prospective Irrigation Strategies in the U.S. Corn Belt.

Water, 11(2447): 1-18, 2019. doi: 10.3390/w11122447

- *Page 121*

Orduña Alegría, M. E.; Schütze, N.; Zipper, S.

A Serious Board Game to Analyze Socio-Ecological Dynamics towards Collaboration in Agriculture.

Sustainability, 12(13): 5301, 2020. doi: 10.3390/su12135301

Supplementary Information:

- *Page 140*

MAHIZ Rulebook

- *Page 156*

MAHIZ Feedback Form

water

MDPI

Article

Evaluation of Hydroclimatic Variability and Prospective Irrigation Strategies in the U.S. Corn Belt [†]

María Elena Orduña Alegría [1,*], **Niels Schütze** [1] **and Dev Niyogi** [2]

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[2] Department of Agronomy and Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Lafayette St, West Lafayette, IN 47907, USA; climate@purdue.edu

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† This paper is an extended version of our paper published in the EGU General Assembly 2019, Vienna, Austria, 7–12 April 2019.

check for updates

Abstract: Changes in climate, land use, and population growth has put immense pressure on the use of water resources in agriculture. Non-irrigated fields suffer from variable water stress, leading to an increase in the implementation of irrigation technologies, thus stressing the need to analyze diverse irrigation practices. An evaluation of 17 sites in the U.S. Corn Belt for two temporal climatic conditions was carried out. It consisted of the analysis of critical hydroclimatic parameters, and the evaluation of seven diverse irrigation strategies using the Deficit Irrigation Toolbox. The strategies included rainfed, full irrigation, and several optimizations of deficit irrigation. The results show a significant change in the hydroclimatic parameters mainly by increased temperature and potential evapotranspiration, and a decrease in precipitation with an increase in intense short rainfall events. Consequently, the simulations indicated the potential of deficit irrigation optimization strategies to increase water productivity above full irrigation and rainfed conditions. In particular, GET-OPTIS for wet soil conditions and the Decision Tables for dry soil conditions seasons. The present study highlights the contributions of atypical weather to crop production and the implications for future management options, and allows specialized regionalization studies with the optimal irrigation strategy.

Keywords: crop-water productivity; irrigation strategy optimization; agroclimatic resiliency; crop-climate decision tools; U.S. Corn Belt

1. Introduction

The spatial and temporal variability of climate, land use, soil degradation, and population growth put immense pressure on water resources. Sustainability and resilience depend strongly on the way managers and consumers adapt to the current and predicted variability. In particular, the intense pressure on food security hinders adequate water resource management, primarily in the face of rainfall vagaries and when agriculture relies on or is expected to rely on irrigation. The agrohydrological dilemma (i.e., securing food production in water scarcity scenarios) was analyzed in several studies focusing on the impacts of climate variability on crop yield (e.g., Niyogi et al. [1], Brumbelow et al. [2], Rosenzweig et al. [3] and Elliot et al. [4]). Studies such as Pereira [5] and Gorantiwar et al. [6] focused on the improvement of irrigation techniques, while Dobernmann et al. [7], Godfray et al. [8] and Rockstrom et al. [9] focused on the prospective future of sustainable agriculture through irrigation availability.

This study focuses on the agricultural production of corn (*Zea mays L.*) in the Corn Belt region of the United States of America (US). Crop yields in the Corn Belt were projected to go down in the future climate as a result of an increase in extreme weather events and increased rainfall variability [10].

Irrigation has the potential to become a globally implemented adaptation strategy in the face of climate change. In the simplest sense, irrigation practices seek to apply water to the soil and plant for effective crop production by influencing stages from germination to yield. Crop simulation models allow investigating outcomes for different management schemes that might increase the yield [11]. One of the main tools to achieve this is irrigation scheduling (a sequence of dates or and times on which water needs to be applied to the crop), can be optimized by mathematical models [12]. A common irrigation strategy, known as full irrigation, is to supply sufficient water to meet with the plant evapotranspiration requirements. Due to the scarce nature of water resources, other strategies were developed, such as supplemental and deficit irrigation, to reduce the agricultural water demand and to divert the resources for alternative uses. Supplemental irrigation is the application of small amounts of water to rainfed crops when rainfall does not meet the plant evapotranspiration requirements, and deficit irrigation is the optimized application of water below the plant evapotranspiration requirements. Both irrigation strategies were thoroughly analyzed and optimized to maximize water productivity and to maintain yields [13,14]. Crop Water Productivity (CWP), defined as crop yield per cubic meter of water consumption [15] is a good indicator of water-agriculture interaction. The CWP function can be used to show the obtainable yield at different levels of applied water. The CWP functions (CWPFs) are characterized by linearly increasing yields with applied water until 50% of full irrigation [16–18]. The relationship becomes curvilinear as applied water increases further, due to losses from increased surface evaporation, runoff and deep percolation. Moreover, local factors, such as soil and irrigation technology, can affect the relation [19]. Furthermore, climate variability has an impact on CWPFs, which highlights the importance of a stochastic approach to irrigation [2]. Recent studies by Evett et al. [11], Raju et al. [12], English et al. [19], Brown et al. [20] and Shang et al. [21] indicate that a detailed and precise irrigation schedule calculated using crop models can optimize the CWP by maximizing irrigation efficiency, reducing costs and environmental impacts. Irrigation scheduling [22] is conventionally based on soil water balance models, where the soil moisture deficit is estimated by the difference between the inputs (irrigation and precipitation) and the losses (runoff, percolation, and evapotranspiration). The adequate water volume to be irrigated varies as a function of actual evaporative demand, for deficit irrigation strategies this is a complex task to achieve because of the day to day variation in climate and crop water demands. The impact of hydroclimatic variability was investigated (e.g., Djaman et al. [23], Badh et al. [24], Gunn et al. [25], Messina et al. [26], Niyogi et al. [27], Panagopoulos et al. [28] and Zwart et al. [29]), and deficit and supplemental irrigation strategies are often promoted as a response to mitigate drought stress on crops [6,13,14,30–32]. However, very few studies evaluated different irrigation strategies in the same location as a measure of hydroclimatic variability and sustainable agricultural productivity. Studies by Niyogi et al. [1], Yang et al. [33], Song et al. [34], and Kloss et al. [31] highlight the ability of crop models to capture the impacts of climate variability on yield considering different sources of uncertainty. Most of the crop models aim to achieve an optimum water supply for productivity, with soil water content being maintained close to field capacity, most commonly via conventional or supplemental irrigation (i.e., 100% of field capacity) [35]. Alternatively, deficit irrigation strategies were developed as an adaptation to limited water availability by estimating the supply of irrigation during the most sensitive growth stages and allowing prioritization of the allocation of resources to these drought-sensitive stages [10,32]. Deficit irrigation strategies aim for a determined lower percentage, typically between 70%–90%, of field capacity [13,30]. The optimal time to irrigate depends on the seasonal water demand pattern which varies by crop, the hydraulic soil characteristics, and the available amount of water [36]. The estimation of the irrigation scheduling is aimed to obtain the highest potential crop yield for a given total seasonal depth of irrigation. However, these estimations are also limited by preconditions of access to a perfect forecast of intraseasonal crop water requirements [37]. As an alternative to such

idealized consideration, optimization approaches based on decision tables or a framework such as the Optimal Climate Change Adaption Strategies on Irrigation Methodology (OCCASION) [38] are available.

Most of the simulation-based studies of deficit irrigation do not consider the variability of important climate parameters, i.e., temperature, evapotranspiration and precipitation, within different temporal scales. The studies mostly focused on all rainfed sites or at irrigated sites with assumption about full field capacity irrigation [14,31,32,39,40]. This highlights the need for multidisciplinary simulations where different irrigation management strategies for corn production are compared and assessed. Therefore, based on the projected changes in water resources availability and the potential of implementation of irrigation technologies in the intense agriculture in the Corn Belt, the objective of this study was to understand the hydroclimatic variability at different temporal scales and to evaluate supplemental and deficit irrigation optimizers under potential water scarcity conditions over locations across the US Corn Belt.

2. Materials and Methods

2.1. Study Area

Corn, the primary US feed grain, accounts for around 500–600 billion tons of production in the US [41,42]. Most of the corn production occurs in the Corn Belt, a region in the US Midwest known for the ideal climate and soil conditions for crop production and intense farming characterized by high fertile soils, high organic soil concentration, timely rainfall, and ample solar radiation. Geographically, the Corn Belt consists of the states of Iowa, Illinois, Indiana, Nebraska, Kansas, Minnesota, Missouri, South Dakota, North Dakota, Ohio, Wisconsin, and parts of Michigan and Kentucky. The region is divided by two large intensively cropped river basins, the Upper Mississippi River Basin and Ohio-Tennessee River Basin and it is located within five water resources regions (Missouri, Arkansas-White-Red, Souris-Red-Rainy, Upper Mississippi, Lower Mississippi, Ohio, and the Great Lakes) [28].

County-level data of corn yield and climatic variables were assessed and used following Niyogi et al. [1] and Liu et al. [43]. This provided a spatially representative data set for 17 sites within the US Corn Belt. Information regarding these sites is provided in Figure 1 and Table 1.

Table 1. Summary of the 17 study sites.
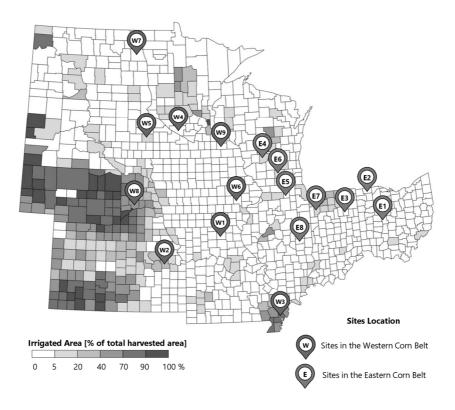
#	Code	Site	County	State	Area Harvested [×1000 ha]	Irrigated Area [%]
1	W1	Kirksville	Adair	Missouri	5.73	NDD
2	W2	Topeka	Shawnee	Kansas	15.29	31
3	W3	New Madrid	New Madrid	Missouri	27.51	79
4	W4	Olivia	Renville	Minnesota	43.97	<0.1
5	W5	Brookings	Brookings	South Dakota	47.87	8
6	W6	Iowa City	Johnson	Iowa	55.44	NDD
7	W7	Grand Forks	Grand Forks	North Dakota	56.30	4
8	W8	Columbus	Platte	Nebraska	75.72	67
9	W9	Rochester	Olmsted	Minnesota	115.32	<0.1
				Total	443.16	19
10	E1	Marysville	Union	Ohio	8.88	NDD
11	E2	Toledo	Lucas	Ohio	29.02	NDD
12	E3	Huntington	Huntington	Indiana	30.41	<1
13	E4	Baraboo	Sauk	Wisconsin	32.65	19
14	E5	DeKalb	DeKalb	Illinois	50.44	<0.01
15	E6	Beloit	Rock	Wisconsin	60.59	7
16	E7	Rensselaer	Jasper	Indiana	62.99	9
17	E8	Tuscola	Douglas	Illinois	104.2	<1
				Total	379.19	5

NDD: not disclosed data; 1 ha = 10,000 m^2.

Figure 1 shows a representative county outline map of the US Corn Belt with the distribution of irrigation intensity. The counties with the most irrigated area are in the southwest of the Corn Belt, and the center or eastern region is almost entirely rainfed agriculture with no irrigation reported. The study sites (Table 1) are divided into two parts across the Corn Belt, the Western (red) and Eastern (blue). The sites in the Western Corn Belt reported more use of irrigation technologies with two counties (New Madrid, MO, and Platte, NE) with more than 60% irrigated area. On the contrary, the sites located in the Eastern Corn Belt have mainly rainfed agriculture with less than 10% irrigated area with the exception of Baraboo, WI. This irrigation intensity can be considered representative of the ground reality across the Corn Belt.

Figure 1. Map showing the reported irrigated area by county along in the US Corn Belt and the location of 17 study sites (2012 NASS-USDA [44]).

2.2. Data

To analyze the impacts of climate variability on crop yield, historical (1981–2010) and future climatic conditions (2041–2070) were considered for the 17 study sites. The data required was compiled as input the modeling framework discussed in Section 2.4, details can be found in Supplementary Material SI. The data sets included were the daily meteorological data (minimum temperature, maximum temperature, and precipitation) for the historical climatic conditions from the National Centers for Environmental Information (NCEI, [1]). The future climate condition was obtained from the National American Regional Climate Change Assessment Program (NARCCAP, [45]) from the

dynamically downscale product from the MM5 with the Hadley Centre Climate Model version 3. Further information about this data set can be found in Mearns et al. [46–48], and Horton et al. [49]. The irrigation strategy model requires information about evapotranspiration water loss. Because of the lack of this information for the historical climatic conditions and to keep consistency between different time scales, the daily potential evapotranspiration was calculated with the FAO ETo Calculator [50] using the Penman-Monteith equation. Additional agronomic information was required which was compiled from the National Corn Handbook [51], which included the extent of the growing season of around 130 to 150 days across the Corn Belt. A period of 150 days was considered and divided into four phenological stages. These stages included: initial planting/germination (30 days), crop development (40 days), mid-season (50 days) and late development (30 days). The growing season dates were specifically chosen for each site from the reported dates in the Field Crops Usual Planting and Harvesting Dates [52], for the historical climatic conditions from 1997 and for the future climatic conditions from 2010.

2.3. Irrigation Strategies

When this study was conducted, only seven irrigation strategies were integrated into the Deficit Irrigation Toolbox (DIT) described in Section 2.4. The present study seeks to analyze rainfed, full and deficit irrigation strategies with diverse management optimization to assess these strategies relative to the on-going practices in the study sites. Therefore all the seven irrigation strategies were considered. These include (i) no irrigation (rainfed system), (ii) full (supplemental) irrigation, and (iii) five deficit irrigation strategies. These seven strategies were:

1. **Rainfed** (**S1_RF**): consists of no water application to simulate rainfed agriculture. This is used as a reference and is expected to produce a lower limit of yields.
2. **Full supplemental irrigation** (**S2_SFI**): triggers the irrigation of a predefined amount of water when the soil water deficit is above a certain threshold. The full irrigation assumes an unlimited amount of water availability. This strategy is expected to consume the maximum amount of water while achieving the yield potential.
3. **Simple Deficit irrigation** (**S3_DI**): triggers irrigation of a predefined amount of water when the soil water deficit is above a threshold which already causes drought stress for the crop. This irrigation strategy is a simple implementation of deficit irrigation. It is expected that **S3_DI** consumes less water than **S2_SFI**, but full irrigation cannot be applied when water availability is constrained or limited. **S3_DI** serves as a non-optimized deficit irrigation strategy which is compared with other optimized deficit irrigation strategies.
4. **Constant supplemental irrigation in a fixed schedule** (**S4_CFS**): realizes a fixed application depth of water for a fixed irrigation interval of days (e.g., 7 days between applications). This deficit irrigation strategy can deal with limited given water volumes but implements a non-optimized strategy which is expected to achieve a low yield.
5. **Optimized deficit irrigation with decision table** (**S5_ODT**): is a closed-loop irrigation control based on information about the available water and the water deficit in the soil. For daily decisions, a decision table is optimized for maximizing water productivity. The optimizer was implemented using Evolution Strategy with Covariance Matrix Adaptation (CMA-ES) for nonlinear function minimization, Version 3.61. Beta [53].
6. **Optimized deficit irrigation with a decision table and phenological stages** (**S6_ODTph**): implements a modified decision table based on the crop response to water stress at the specific phenological stages throughout the growing season. The optimizing process was also implemented using CMA-ES.
7. **Optimized deficit irrigation with Global Evolutionary Technique for Optimal Irrigation Scheduling (GET-OPTIS)** (**S7_GO**): is an open-loop irrigation control that implements a general irrigation calendar which is valid for all growing seasons of a considered time series.

The implementation is based on the tailor-made evolutionary GET-OPTIS algorithm developed by Schütze et al. [38]. This strategy allows for a simpler application in practice than **S5_ODT** and **S6_ODTph** since no information about the water deficit in the soil is required.

S1_RF, **S2_SFI**, and **S3_DI** were evaluated using the workflow outlined in Figure 2. The remaining strategies were implemented based on the workflow shown in Figure 3. Consequently, for the optimized strategies the computational demand is significantly higher. Furthermore, **S2_SFI**, **S3_DI**, **S5_ODT**, and **S6_ODTph** strategy require sensor information about either climate and/or soil variables. On the contrary, **S1_RF**, **S4_CFS**, and **S7_GO** strategy are the cheapest and easiest to use.
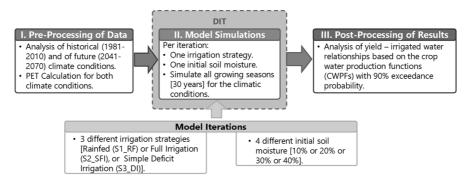
Figure 2. Model framework for the basic irrigation strategies (S1_RF, S2_SFI, S3_DI).
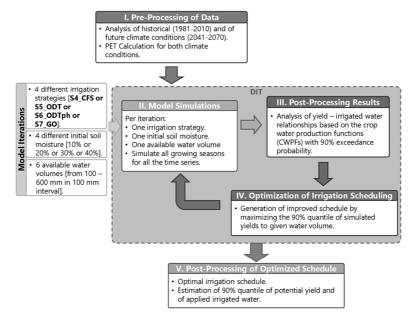
2.4. Model Framework

The assessment of diverse irrigation strategies was modeled using the DIT [54], an open-source software to analyze the crop yield response to climate and soil variability, as well as water management practices. The DIT considers several irrigation scheduling strategies and different crop models such as AquaCrop [18] and Soil-Water Balance (SWB) [55]. The stochastic relationship between simulated yield and irrigated water also known as Stochastic Crop Water Production Functions (SCWPF), the main result of the DIT, is an effective tool for risk analysis on irrigation demand [37]. The framework used in the DIT was applied and validated in different field studies (e.g., Grundmann et al. [56], Schütze et al. [57], and Gadédjisso-Tossou [54]).

For this study, the Soil-Water Balance Model (SWB) [55] was combined with seven different irrigation strategies available in the DIT. The SWB model is a relatively simple model that simulates the yield response based on the water deficits in the soil storage. The choice of this model was to avoid confounding in the interpretation of the results with other complex models and can be undertaken in a future study with more available data. Despite its simplicity, the model demonstrated reliable performance in previous studies (e.g., Rao et al. (1988 [58], 1992 [59]), Panigrahi et al. [60], Khan et al. [61] and Gassmann et al. [62]). The ability of the model to be really responsive to hydroclimatic variability in one of the inherent strengths and needs in choosing this modeling system.

Each irrigation strategy implementation followed a certain framework. For the first three irrigation strategies (S1_RF, S2_SFI, S3_DI), the workflow considered in this study is shown in Figure 2. The first framework mainly consists of three phases: I. Pre-Processing of the data for both the historical and future climatic conditions, including the calculation of daily potential evapotranspiration; II. Model simulations for multiple configurations within the DIT for the growing seasons within the climatic conditions assuming a specified initial soil moisture condition; III. Post-processing of the results by analyzing the SCWPFs within the 90% exceedance probability. For the other strategies (S4_CFS, S5_ODT, S6_ODTph, S7_GO) the framework outlined in Figure 3 was used.

Figure 3. Model framework for the optimized irrigation strategies (S4_CFS, S5_ODT, S6_ODTph, S7_GO).

Similar to the first three phases shown in Figure 2; an additional iteration for limited available water volume between 100 to 600 mm. The incorporation of optimization phases IV and V to account for robustness as the optimizer maximizes a larger quantile (e.g., 90%) of the yields of the simulated scenarios to ensure high water productivity.

The optimization step is implemented using various global, computational demanding optimization techniques (Section 2.3). This proposed framework allows for the risk analysis and assessment of both historical and climate change scenarios within different conditions of water availability. The product of these model simulations is the SCWPFs, (i.e., the stochastic relationship of simulated yield and irrigated water), which represent the risk pattern for a specific irrigation location and certain initial and boundary conditions [63].

2.5. Experimental Design of Model Simulations

The present study undertook multiple simulations for each site and climatic conditions. The experimental design of each simulation follows the sequence shown in Figure 4. This sequence comprised of four steps: (1) The model simulations were carried out resulting in 108 simulation results per site for each climatic conditions, (2) The analysis of these results based on the location within the US Corn Belt, (3) The analysis of the main hydroclimatic parameters to better understand the changes on the simulated yields, (4) The final evaluation of each strategy for both historical and future climatic conditions as well as performance metrics of the irrigation strategy model based on the reported annual yields in the historical climatic conditions.

As was described previously, the model simulations for each study site comprised of seven different irrigation strategies, each analyzed with four different initial soil moisture conditions. For the first three irrigation strategies (S1_RF, S2_SFI, S3_DI) each strategy-soil moisture iteration was modeled with only one available water volume and for the remaining four strategies (S4_CFS, S5_ODT, S6_ODTph, S7_GO), each strategy-soil moisture iteration was modeled with six different available

water volume to irrigate. This resulted in 108 simulations for each site or a total 1836 simulations for each 30 year long climatic conditions in the US Corn Belt. These results were then grouped depending on the location of the site within the US Corn Belt, as each region had different implementation of irrigation. The Western Corn Belt reported the most irrigation applied primarily in Kansas and Nebraska. The Eastern Corn Belt reported very little irrigation. In the next step, a hydroclimatic analysis of the main parameters (i.e., temperature, precipitation, and potential evapotranspiration) was carried out. This aimed to further understand the changes between both historical and future climatic conditions and the impacts on yield and water resources availability. The last step was the evaluation of the model simulations, first for the performance of the model based on the annual yields on the historical climatic conditions and lastly, a comparison of the best performing strategy (i.e., higher potential yield with less applied water) within all the strategies considered.
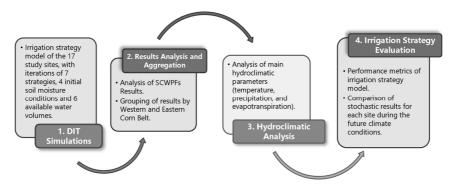
Figure 4. Main Steps of the Experimental Design of Model Simulations.

2.5.1. Hydroclimatic Variability Analysis

The hydroclimatic data analyzed for each site was daily precipitation, maximum and minimum temperature, solar radiation and the estimated potential evapotranspiration. The Corn Belt, particularly the Eastern region, is known for its suitability for rainfed agriculture, nevertheless previous studies (e.g., Alter et al. [64], Karl et al. [10], Gunn et al. [25], Pryor et al. [65], Djaman et al. [23] and Dai et al. [66]) analyzed the impact of the past and projected hydroclimatic changes on the food production in the Midwest US. To help offset the reliance on rainfed agriculture, studies such as Van Dop et al. [67] project an increase in the number of counties within the U.S. where the optimal yield could be improved by the application of irrigation, making this technology a profitable investment. For both historical and future climatic conditions, the main hydroclimatic parameters (average temperature, total precipitation and potential evapotranspiration) were analyzed within the months of April to September which comprised the common 150 days of the growing season within the US Corn Belt. The differences between each region of the Corn Belt and each time series were analyzed.

2.5.2. Model Performance Metrics

Model evaluation metrics assess goodness of fit between model predictions and data. One widely used performance metric is the Mean Absolute Error (MAE). The MAE compares simulated yield with the relative observed yields for each site. This was calculated as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |Y_s - Y_o| \tag{1}$$

where Y_s is simulated yield and Y_o is the reported data. The advantage of using MAE is not only that it is easy to interpret but also allows a comparison with previous studies (e.g., Liu et al. [43] and Niyogi et al. [1]) where the same data sets were evaluated with different crop models.

2.5.3. Evaluation of Irrigation Strategies

The evaluation of the model simulations of each irrigation strategy was based on two limits to assure a true optimization of irrigation application. These two limits were: (i) The optimal conditions for irrigation application based on the simple deficit irrigation estimation, which defines the maximum volume of irrigated water that is not exceeded and (ii) the optimal rainfed conditions, which defines the minimum optimal yield that needs to be achieved. As a result, the simulated results must display a higher potential yield than the rainfed (S1_RF) and higher savings (less irrigated water applied) as compared to the simple deficit irrigation (S3_DI) strategy.

3. Results and Discussion

3.1. Hydroclimatic Variability Analysis

The monthly distribution within the growing season of hydroclimatic parameters: temperature, precipitation, and evapotranspiration in the historical and future climatic conditions are shown in Figure 5, which consists of two sets of plots. The left side (plots a, b, and c) show the historical climatic conditions and the right side (plots d, e, and f) show the future climatic conditions. Each plot is described by a colored central box (blue for Eastern, and red for Western Corn Belt) that represents the distribution of the data where the first and third quartile are the lower and upper boundary lines respectively and the central point indicates the median. The vertical lines extending from the box indicate the data outside of the main quartiles. The outsiders represent the variability within the years and the dotted lines represent the average trend for each parameter in the sites located in each region of the US Corn Belt.

Considering the changes in temperature in both historical and future climatic conditions, the variability within the sites in the Western Corn Belt is higher than in the sites located in the Eastern Corn Belt. The trend in the future growing seasons seems to change, where it is expected a warmer and earlier spring and lower temperatures during summer. The warming in the early months has already changed the dates of the growing season in each county independently by around 12 days longer than it was a century ago [68]. It is estimated an overall warmer temperature during the growing season which could affect not only corn agriculture but other productive crops. A more intensive analysis of the temperature in the Midwest US performed by Dai et al. [66] showed that the early growing season average temperature increased at a rate of 0.15 °C/decade overall, showing different trends for minimum and maximum temperature as well as maximum solar radiation.

Precipitation in both historical and future climatic conditions showed to have a wider inter-annual stochastic variation (i.e., the data outside the central box show a significant increase) from site to site from all the other climate parameters. This randomness could be explained by the increase in short duration heavy rainfalls that are predicted across the US Corn Belt. These extreme rainfall events show an increasing trend, even though the average precipitation showed a general decreasing trend from April to July in the Eastern Corn Belt and throughout all the growing season in the Western Corn Belt. Van Wart et al. [69] demonstrated that the sites located in the Western Corn Belt were more frequently subjected to an episode of transient and erratic rainfall in the critical development stage leading to extra fieldwork, such as drying crops or even bigger yield lost.

The future climatic conditions show lower values of average solar radiation (from the NARCCAP data set) which results in the lower estimation of potential evapotranspiration based on the Penman-Monteith equation. The maximum obtainable yield is reached only when enough water is provided to satisfy crop requirement; hence, irrigation is triggered when the crop has not enough water to meet the maximum evapotranspiration requirements [19]. Climatic variability between

different locations have a significant impact on the yield production, due to the interaction of precipitation, potential evapotranspiration and plant growth requirements. In particular, the amount of water required by maize throughout the growing season depends on the evaporative demand of the atmosphere and water availability [18]. The difference between the two climatic conditions (historical vs future) coincides with the temperature and precipitation changes which connote significant variations of solar radiation, wind velocity, and humidity. Further studies such as that by Basso et al. [70] analyzed the impact of this change in evapotranspiration for the current seeds used in the Corn Belt and concluded that the current high yield can be obtained when the water supply is constantly between 500 to 700 mm for the growing season.
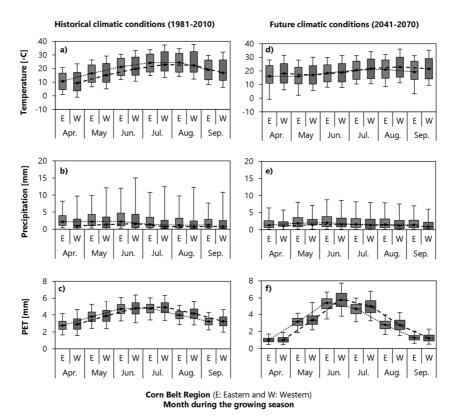
Figure 5. Box-and-whisker plots of the monthly trends of the hydroclimatic parameters in the historical (**left side a to c**) and future (**right side d to f**) climatic conditions for the sites located in the Eastern Corn Belt (blue) and the sites located in the Western Corn Belt (red).

3.2. Model Performance Metrics

The mean absolute error (MAE) was used to assess the performance of the irrigation strategy model.

The MAE (Table 2) summarized the overall performance of the model for each site. For the sites located in the Eastern Corn Belt, the model performed slightly better with an average MAE of 1.7 tons/ha where for the sites located in the Western Corn Belt the average MAE is 2.02 tons/ha. Previous studies by Liu et al. [43] and Niyogi et al. [1] used the same onsite climatological data with

three different crop models: the Hybrid-Maize [33], the Decision Support System for Agrotechnology Transfer (DSSAT) [33] and the Integrated Science Assessment Model (ISAM) [63] in order to assess the impact of model complexity on simulated corn yield in response to climate change. The accuracy of the implemented model in this study shows similar prediction accuracy to the Hybrid-Maize model which was the best of the three models used and was also the simplest crop model. These 17 case studies results provide additional confidence in using the Deficit Irrigation Toolbox to achieve useful model responsiveness to high hydroclimatic and spatial variability.

Table 2. Mean absolute error (MAE, tons/ha) of simulated corn yields in the historical climatic conditions.

Site	Code	Observed Yield [tons/ha]		Predicted Yield [tons/ha]		Mean Absolute Error [tons/ha]
		Average	Std. Dev	Average	Std. Dev	
New Madrid	W3	9.72	1.23	8.87	1.64	1.78
Topeka	W2	7.77	1.46	7.53	1.83	0.94
Kirksville	W1	6.96	2.10	7.24	1.52	2.11
Columbus	W8	9.08	1.85	9.30	2.04	2.16
Brookings	W5	7.25	2.07	7.33	1.87	2.47
Grand Forks	W7	5.96	1.67	6.86	1.87	1.94
Iowa City	W6	8.89	2.16	7.52	1.77	2.23
Olivia	W4	9.51	2.08	9.72	1.83	1.49
Rochester	W9	9.51	2.07	8.99	2.39	2.11
Baraboo	E4	8.42	1.37	8.50	1.48	1.40
Beloit	E6	8.87	1.52	8.91	1.84	1.21
DeKalb	E5	9.96	1.62	9.84	2.59	1.98
Rensselaer	E7	8.93	2.00	8.61	2.20	1.98
Tuscola	E8	9.69	1.78	9.29	2.27	1.76
Huntington	E3	8.83	1.70	8.29	2.14	1.52
Marysville	E1	8.49	2.01	9.14	1.81	2.04
Toledo	E2	9.39	1.68	9.55	2.24	1.69

3.3. Results of Evaluation of Irrigation Strategies
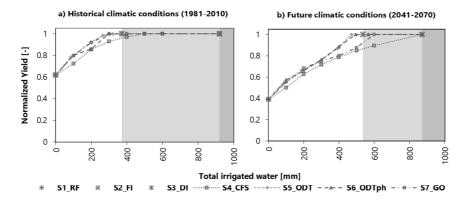
Yield development is impacted by water stress, which was different across sites and the historical and future climatic conditions. Following the experimental design, for every study site, the stochastic crop water production functions (SCWPFs) were estimated based on the limited available water volumes. Figure 6 shows an example of the simulation results for the site in Topeka, KS (W2) for both time series with initial soil moisture of 20%. The different shades of grey in Figure 6 represent the level of optimization achieved by the strategies, where the SCWPF found in the white area are the optimal simulations based on the evaluation metrics (Section 2.5.3). The results in the grey areas show only water saving compared to the full supplemental irrigation.

The results in all 17 study sites indicate that water availability was enough in both historical and future climatic conditions to grow corn under rainfed conditions with a very low yield and with high variability between years. Also, all strategies show significantly different SCWPF in the different soil moisture analyzed. The impact of the hydroclimatic variability between the historical and future climatic conditions is shown simply by the simulated yield with the rainfed strategy (S1_RF). Where the potential yield decreased around 20%, highlighting the need for future optimized irrigation strategies that consider limited available water.

To summarize the main findings of the evaluation of the diverse irrigation strategies, for the case of the constant supplemental irrigation in a fixed schedule strategy (S4_CFS) an improvement in yield can be seen only above rainfed conditions, although small water savings compared to deficit irrigation strategies can be seen only in wet soil conditions (i.e., above 30% initial soil moisture). The decision tables and GET-OPTIS optimizers (S5_ODT, S6_ODTph, S7_GO) showed better results within all the study sites. Both optimizers increased water productivity when compared to non-optimized irrigation strategies. GET-OPTIS (S7_GO) showed better results for wet soil conditions with higher precipitation variability and the Decision Tables performed better for dry soil conditions with high precipitation variability. In particular, the optimized deficit irrigation with decision table strategy (S5_ODT) and

with phenological stages strategy (S6_ODTph) showed improvement in all soil conditions in the historical climatic conditions with more than 50 mm savings of irrigated water. The results during the future climatic conditions demonstrate that the variability within the hydroclimatic parameters affects differently each location, resulting in variable water demands for the entire region.
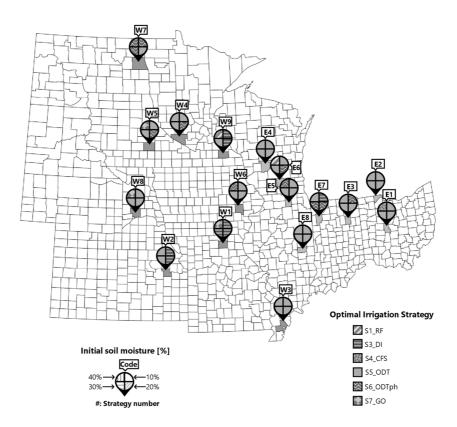
Figure 6. 90% Quantile of Stochastic Crop Water Production Functions for the site in Topeka, KS (W2) for (**a**) historical and (**b**) future climatic conditions with initial soil moisture of 20%.

The 90% quantile of Stochastic Crop Water Production Functions (SCWPFs) of the study sites are significantly different at several levels of irrigation with a proportional increasing trend with the available volume, where a higher level of irrigated volume is required for dry soil conditions. In wet soil conditions (40% initial soil moisture), the irrigation strategies have no impact on the yield, showing the importance of plant-soil moisture data to achieve precise irrigation scheduling. In all locations, stochastic variability between years showed to be higher at low levels of irrigation. This was evidently improved by GET-OPTIS and Decision Tables optimizers. These optimizers performed better for the climates with low and variable rainfall were the irrigation can become the stable source of water for the plant at the most important stages of crop development, the vegetative and reproductive. Plots of each soil moisture-initial conditions for all the 17 study sites are presented in Supplementary Material SII.

Figure 7 shows the evaluation of all the simulation results during future climate conditions. The optimal performing strategy, based on the highest achievable yield with the lowest applied water, is shown for each soil moisture conditions considered.

A detailed evaluation of the optimal irrigation strategy is shown in Supplementary Material SIII, where the percentage of improved yields and water savings are shown based on the two limits set to ensure the optimization of irrigation strategies. Regarding the improvement in the potential yields, Tuscola, IL (E8) for up to 85% in dry soil conditions and 21% for wet soil conditions. Topeka, KS (W2) also show the largest improvement, with more than 70% in dry soil conditions and 12% in wet soil conditions. Regarding irrigated water savings, Huntington, IN (E3) had more than 90 mm in savings in dry soil conditions and Rensselaer, IN (E7) and Toledo, OH (E2) had around 100 mm in savings for wet soil conditions. Grand Forks, ND (W7) and Columbus, NE (W8) showed improvements above the 100 mm for dry soil conditions and wet soil conditions respectively. In both locations (W7 and W8) irrigation technologies are already being implemented, highlighting the potential of deficit irrigation technologies to maximize water productivity. The sites located in the center of the Corn Belt (i.e., Rochester, MN (W9) Baraboo, WI (E4), and Beloit, WI (E6)) in wet soil conditions showed no improvement in yields compare to the rainfed strategy S1_RF.

Figure 7. Optimal irrigation strategy for every initial soil moisture [10–40%] for future climatic conditions.

3.4. Summary of Discussion

Recommendations for full or limited irrigation differ in practice and literature, hence the evaluation of a wide range of irrigation strategies was carried out. Results highlight the potential of deficit irrigation to be beneficial for crop yield, yet also considering rainfed and supplemental irrigation approaches. The optimization of deficit irrigation strategies increased water productivity for the historical climatic conditions as well and showed potential to conserve water and improve yield productivity for the future climatic conditions. In years of predicted water scarcity, yields of at least 60% could be achieved with 200 mm of irrigation water at very high reliability when optimization strategies are used. In the same conditions, the rainfed strategy achieved less than 40% in the study sites of the Corn Belt. The simulated level of irrigated water coincides with the optimum crop water productivity values reported for irrigated maize by Zwart et al. [29], demonstrating the high risk of non-optimized schedule for sites with high climate variability. Based on the performance of the strategies, the future investment in irrigation equipment can be expected to happen primarily in the sites located in the Eastern Corn Belt within Ohio and Great Lakes water resource region. The sites located in the Western Corn Belt, where there is already irrigation, are expected to continue adapting for efficient irrigation practices to minimize the impact of the water demand on other vital demands. The exception of Iowa and Minnesota in the Upper Mississippi water resource region where the implementation of irrigation did not show a significant improvement of the rainfed agriculture for it to be considered a profitable investment base merely on the gains in simulated yields.

3.5. Limitations

The irrigation strategy model has several limitations. The first concern was that the observed data available was for only rainfed conditions, therefore the model showed slightly different results for the counties where irrigation is already being applied. Additionally, the simplicity of the SWB has inherent limitations predicting crop yields for the different growing season dates. Another simplification of our experimental designed is the choice of 10% ranges of initial soil moisture percentage due to the lack of data in different temporal scales. Despite such limitations, the model framework, as well as the experimental analysis proved its high usefulness and big potential for further specialized studies.

4. Conclusions

This study aimed to analyze the hydroclimatic variability at different temporal scales and to evaluate supplemental and deficit irrigation optimizers under potential water scarcity conditions over US Corn Belt, where rainfed conditions are expected to change and adaptations strategies are needed. The experimental design using the DIT were used to integrate different irrigation strategies into a parsimonious crop model that boosts crop efficiency and reduce the impact on water resources in a changing climate. The previously favorable hydroclimatic conditions in the Corn Belt for rainfed agriculture are estimated to change, opening the opportunity for mitigation strategies. The results show a decreasing trend in seasonal precipitation but an increasing trend in temperature and potential evapotranspiration for future growing seasons. The spatial and temporal variability of the precipitation changes shown by the increased stochastic variations suggests the need for additional catchment capacities and an increase in the water demand for agricultural production affecting all the other water demands. Higher hydroclimatic variability implies higher risks yield reduction, consequently, the simulations showed the great potential of deficit irrigation optimization strategies to increase the water and yield productivity for future growing seasons. The Decision Tables and GET-OPTIS optimizers showed good results for the study sites, GET-OPTIS showed better results for wet soil conditions with higher precipitation variability and the Decision Tables performed better for dry soil conditions seasons with high precipitation variability. The regionalization of more studies of areas surrounding the studied sites where a more complex crop model with specialized soil and climate data can be done based on the optimal irrigation scheduling strategy produced by this study.

Abbreviations

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

CWP	Crop Water Productivity
US	United States of America
SCWPF	Stochastic Crop Water Production Functions
SWB	Simple Soil-Water Balance Model for Irrigated Areas
CMA-ES	Evolution Strategy with Covariance Matrix Adaptation
GET-OPTIS	Global evolutionary Technique for Optimal Irrigation Scheduling
S1_RF	Rainfed irrigation
S3_DI	Simple deficit irrigation
S4_CFS	Constant supplemental irrigation in a fixed schedule
S5_ODT	Optimized deficit irrigation with decision table
S6_ODTph	Optimized deficit irrigation with decision table with phenological stages
S7_GO	Optimized deficit irrigation with GET-OPTIS
MAE	Mean Absolute Error

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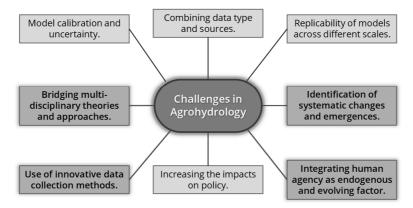
Figure 1. Current challenges in agrohydrology (adapted from Elsawah et al. [10]). Our study focuses on the challenges marked in green.

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.
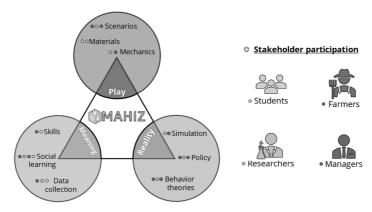
Figure 2. Adapted Triadic Game Design.

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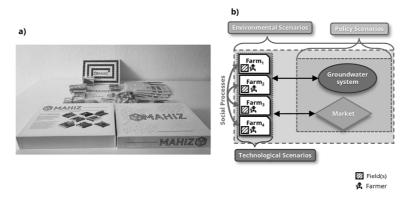
Figure 3. MAHIZ: (**a**) Board game components and (**b**) Agrohydrological system considered.

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
Game session	Date (dd.mm.yy).
Round number	1...12.
Scenarios	Climate and policy scenarios of each round. The same sequence was used for every game session.
Identifier	Observation number 1...113.
Color	Chosen color by players. No other personal data from participants was collected.
Rain dice results	(1...6). Weather forecast.
Sun dice results	(1...6). Harvest factor.
Technology implemented	Irrigation/Hybrid seeds/None/Both.
Level—Irrigation	Number of drops taken from the communal well by each player.
Level—Hybrid seeds	0...3.
Maize produced	Number of maize pieces produced.
Profit	Money earned based on maize pieces sold and negotiations between players.
Communication	Active/Passive
Trust	Open/Closed
Competence	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
Comments and Observations	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).
Feedback	Opinion about the gameplay and structure of game sessions.
New Knowledge	Yes/No.
Behavior	Static or dynamic decision-making processes experienced throughout the game.
Ranking of behavior theories	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.
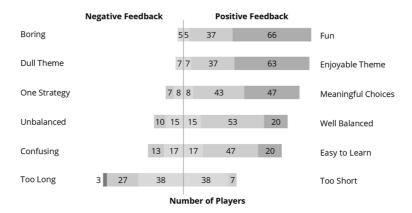
3. Results

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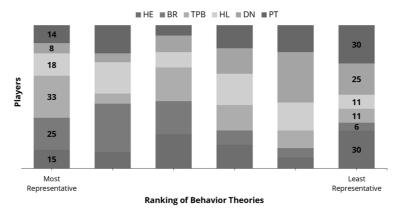
> *"I like the idea about a board game to simulate the decision making process in agriculture. The more you learned about working together but also being selfish, the more opportunities you have to win."*—Homo Economicus Player [21.11.19]

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.
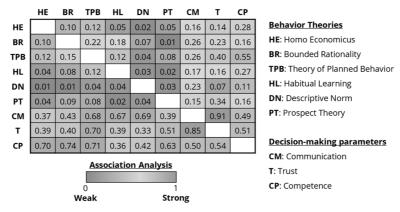
Trust: Power dynamics were observed between upstream (first player) and downstream (last player) players in each round. Downstream players often started the negotiation process where trust was a critical parameter. Relatedness (i.e., pre-existing friendship between players) increased the influence on 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) ($\tau = 0.63$).

	HE	BR	TPB	HL	DN	PT	CM	T	CP
HE		0.10	0.12	0.05	0.02	0.05	0.16	0.14	0.28
BR	0.10		0.22	0.18	0.07	0.01	0.26	0.23	0.16
TPB	0.12	0.15		0.12	0.04	0.08	0.26	0.40	0.55
HL	0.04	0.08	0.12		0.03	0.02	0.17	0.16	0.27
DN	0.01	0.01	0.04	0.04		0.03	0.23	0.07	0.11
PT	0.04	0.09	0.08	0.02	0.04		0.15	0.34	0.16
CM	0.37	0.43	0.68	0.67	0.69	0.39		0.91	0.49
T	0.39	0.40	0.70	0.39	0.33	0.51	0.85		0.51
CP	0.70	0.74	0.71	0.36	0.42	0.63	0.50	0.54	

Association Analysis

0 — Weak   1 — Strong

Behavior Theories

HE: Homo Economicus
BR: Bounded Rationality
TPB: Theory of Planned Behavior
HL: Habitual Learning
DN: Descriptive Norm
PT: Prospect Theory

Decision-making parameters

CM: Communication
T: Trust
CP: Competence

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).
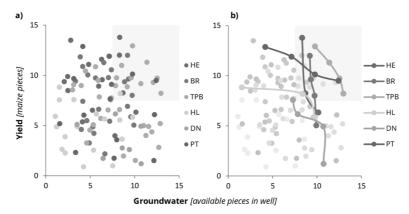
3.4. Analysis of Socio-Hydrological Dynamics

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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Conflicts of Interest: The authors declare no conflict of interest.

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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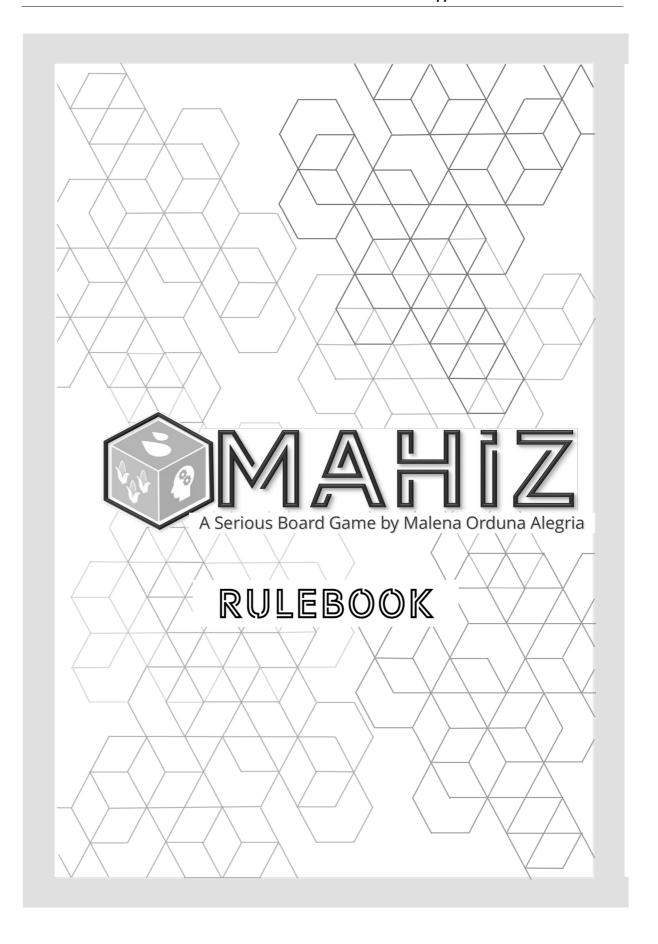
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MAHIZ

A Serious Board Game by Malena Orduna Alegria

RULEBOOK

RULEBOOK

MAHiZ

Game definitions

- **Maize agriculture**: sustainable production of **Maize** (*Zea mays L.)* that depends on the correct application of production inputs that will sustain the environment as well as agricultural production.

- **Irrigation**: application of controlled amounts of water to plants at needed intervals.

- **Hybrid seed**: seed produced by cross-pollinated plants. Hybrids are chosen to improve the characteristics of the resulting plants, such as better yield, greater uniformity, improved color, and disease resistance.

- **Region's prominence**: the state of the region (all farmers) being important or noticeable based on their **Maize** production and environmental quality.

- **Precipitation**: water that falls from the clouds towards the ground and that can be taken by the plants to grow.

- **Evapotranspiration**: water lost from plants that determine their growth and yield rate.

- **Cooperation**: the act of working together with someone or doing what they ask you.

- **Communication:** to share information with others by speaking, writing, moving your body, or using other signals.

- **Yield**: in agriculture, crop yield (also known as "agricultural output") refers to both the measure of the yield of a crop per unit area of land cultivation, and the seed generation of the plant itself.

- **Flash flood**: a sudden and severe flood lasting for minutes and affecting the growth plant and land for longer period of time.

- **Deficit irrigation:** optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop. It aims at stabilizing yields and at obtaining maximum crop water productivity rather than maximum yields.

2

MAHIZ RULEBOOK

Game idea

Mahiz is a role-playing board game for **2-4 players**, designed to analyze the farmers' behaviors regarding climate change, policy implementations, and technological adaptations in **Maize** agriculture.
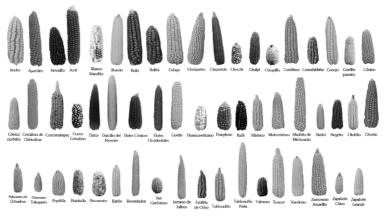
Playing time: 45 min + explanation.

Age: from 12 years.

Maize is one of humanity's greatest agronomic achievements. Today it is the most widely produced crop in the world. **Maize** originated in Mexico, which is home to a rich diversity of varieties that has evolved over thousands of years of domestication. The term "**Maize**" is derived from the ancient Taino word *mahiz* which means "**what nurtures life**".

Some of the 59 native Mexican **Maize** landraces

© CIMMYT Maize Germplasm Bank

As Popol Vuh, the Mayan creation story, goes, the creator gods made the first humans from white **Maize** hidden inside a mountain under an immovable rock. To access this **Maize** seed, a rain god split open the rock using a bolt of lightning in the form of an axe. This burned some of the **Maize**, creating the other three grain colors, yellow, black and red. The creator gods took the grain and ground it into dough and used it to produce humankind.

3

RULEBOOK

MAHIZ

Game description

A small field, an initial farm budget, and basic conditions to grow **Maize**, is all the new farmers have at the start of the game. The implementation of irrigation and hybrid seed technologies offer farmers abundant possibilities to improve their farm production and the overall region's prominence. For the definition of terms used during the game – see *Game definitions* (page 2).

Different events happen during the game – see *Description of Event Cards* (page 11), which can influence the weather conditions, availability of resources as well as the policies of technology implementation.

In each of the 12 rounds, farmers can decide their management strategy by implementing technologies and expanding their land – see *Phases Description*, to adapt to the weather variability and the effects of the events. At the end of the game, the winner is the farmer who has established the best farm practices – see *Scoring* (page 11). Victory points are awarded for the number of full fields produced and **Profit** earned.

© freepik

> The farmers are encouraged to discuss and plan as a group each growing season to achieve the best regional production, but there can only one be winner.
> The game is played competitively as well as cooperatively.

4

MAHIZ RULEBOOK

Components

Game boards:
a. 4 individual boards.
b. 1 scoring board.

Dice:
c. Variability of the precipitation (**Rain**).
d. Variability of the evapotranspiration (**Sun**).
e. Variability of the market (**Price**) of **Maize**.

Pieces:
f. 200 **Maize** (**Yield**) with bag.
g. 13 field squares.
h. 1 Starting player marker.
i. 12 Farmer markers (3 in each color)
j. 32 Blue drops (**Rain**)
k. 32 Yellow drops (**Sun**)
l. 20 Black drops (**Well**)
m. 20 Green drops (**Plant**)
n. Money bills.
o. 5 squared transparent boxes
p. 8 Victory Crowns

Cards:
q. 18 System Event.
r. 18 Weather Event.
s. 4 Summary cards

Levels:
t. 4 Initial levels: Irrigation.
u. 4 Initial levels: Hybrid Seed.
v. 4 Improved levels: Technological Advance.
w. 4 Improved levels: Biological Advance.
x. 4 Improved levels: Deficit Irrigation

5

RULEBOOK

Setup

1. The starting player marker is assigned to the person who has eaten corn or bought a product made out of corn most recently – see *Some of the many uses of corn* (page 15) for more inspiration. The starting player marker is automatically passed on to the farmer to the left (clockwise order) at the end of each round.

2. Each farmer chooses a color and takes the individual board, the corresponding token markers, a field token and the initial level of technologies. Each farmer gets $100,000 in money bills.

3. The farmer marker is placed on the scoring section. The initial levels are place in each individual board with the levels side turned down, the technological markers are placed under to the initial cost of each technology and a field token is placed on the first field space on the individual board.

Example of a 4 players game

4. The initial level of resources, meaning the number of drops in each box, is set up the following way:

Number of Players	Rain Drops
2	12
3	18
4	24

Number of Players	Sun Drops
2	12
3	18
4	24

Number of Players	Well Drops
2	5
3	9
4	13

Number of Players	Plant Drops
2	10
3	15
4	20
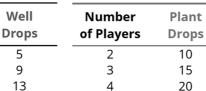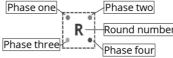
Distribution of resources. It is advisable to place the compartments as is show in the image.

5. 4. Sort the event cards first according to the color (purple for **Weather Events**, orange for **System Events**) and second according to the game variation that is been played. Mahiz can be played in two different variations:

   I. Data collection: The Weather and System Events cards with the round and phase marker are selected and the rest are discarded. Then each deck is ordered by ascending number and place where all player can see them.

   Phase one   Phase two
   R — Round number
   Phase three   Phase four

   II. Collective Learning: Each deck is shuffled and place where all player can see them.

6

Play of the game

The game consists of 12 rounds. Each round follows the same pattern and consists of three phases, which are followed by a fourth phase only after rounds 4, 8 and 12.

At the beginning of each round, turn over the top card of the Weather and System Event decks. The effect of the card applies to all farmers and it modifies the starting level of the **Well** for one turn only.

Phases Description

● **Phase 1: Investment phase**

In order to use the technologies, each player needs to make the decision about investing in the implementation of each technology which can only be done at the beginning of each round. To unlock (turn around) these technologies, each player needs to pay the initial installation costs.

- **Irrigation**: initial costs = $15,000
- **Hybrid seeds**: initial costs = $25,000

Technologies' Initial level

Additionally, each player can expand their farm by buying new extra fields with a cost of $20,000 for each. There is only a limited number of fields available, therefore farmers need to manage their budget carefully.

Investment phase example:
In the first round the red farmer decides to install irrigation technology and pays $15,000, the blue farmer decides to install hybrid seed technology and pays $25,000, the green farmer decides to install both technologies and pays $40,000 and the yellow farmer decides to not install any technologies.
The investment phase occurs only at the beginning of each round.

7

RULEBOOK

MAHIZ

● **Phase 2: Planting phase:**

The farmer with the starting player marker rolls the **Rain dice** and every farmer takes the number of **Rain drops** considering the restrictions from the events and sets them on the **Rain delimited area** in their individual board .

Then each farmer in clockwise order decides whether to implement the technologies previously acquired in investment phase:

• When irrigation technology is applied, the irrigation marker is set to the desired level then the farmer pays the cost of operation accordingly and grabs the **Well drops** and sets them on the **Well delimited area** in their individual board. If the **Well** runs out of drops, then irrigation cannot be applied anymore. If there is one cube, then the farmer must still pay the minimum cost of operation.

⚠ **If the well levels reaches zero due to the use of irrigation, the well loses 1 drop for the rest of the game.**

• When hybrid seed technology is applied, the hybrid seed marker is set to the level desired then farmer pays accordingly the cost of operation and grabs the **Plant drops** and sets them on the **Plant delimited area** in their individual board.

Planting phase example:
*The results of the rolling of the **Rain dice** is 2, therefore all farmers grab two **Rain drops** and sets them in the first compartment in their individual boards. The red farmer decides to implement level 1 of the irrigation technology and pays $10,000, then the red farmer grabs 3 **Well drops** and sets them in the second compartment. The blue farmer decides to implement level 1 of the hybrid seed technology and pays $15,000, then the blue farmer grabs 2 **Plant drops** and sets them in the third compartment. The green farmer decides to implement level 1 of both of the technologies and pays $25,000, then the green farmer grabs 3 **Well drops** and sets them in the second compartment and 2 **Plant drops** and sets them in the third compartment. The yellow farmer cannot implement any technologies because they weren't bought in the previous phase.*

8

MAHIZ

RULEBOOK

● **Phase 3: Harvest Phase:**

The farmer with the starting player marker rolls the **Sun dice** and every player takes the number of **Sun drops** considering the restrictions from the events and sets them on the **Sun delimited area** in their individual board . If hybrid seed technology was applied, then the effect of the level applied in the **Sun** is activated, the farmer grabs the reduced number of **Sun drops**.

> *Harvest phase example:*
> *The results of the rolling of the Sun dice is 4, therefore the red and yellow farmer grab 4 Sun drops and the blue and green farmers, because they implemented hybrid seed technology, only grab 2 Sun drops.*

Yield calculation

Each farmer calculates the amount of **Yield** obtained in the round based on the number of drops that each farmer has in their individual board:

[**Rain drops** + **Well drops** + **Plant drops**] – **Sun drops** = **Maize** Produced (**Yield**)

Each player grabs the amount produced of **Maize** and sets them in the field(s) in the individual board. Each field can hold only 9 **Maize**, if there is not enough space in the available field then the remaining **Maize** is set in the extra seed compartment in the individual board.

> *Yield calculation example:*
> *Based on the drops in the farmers compartment. This growing season the red farmer produced 1 Maize, the blue farmer produced 2 Maize, the green farmer produced 5 Maize and the yellow farmer produced 0 Maize. When a farmer produced negative Yield then this farmer hast to reduce the existing Maize from previous rounds.*

Extra Seeds

When there is **Maize** in the extra seed compartment in the individual board, the farmer must wait for the next investment phase and buy a new field, then the player can pay $1,000 for 3 **Maize** to grow these extra seeds in the fields.

9

RULEBOOK

> **Extra seed example:**
> In the next round the yellow farmer got 2 more **Maize**, achieving a total **Yield** of 2 **Maize**, the red farmer got 4 more **Maize**, achieving a total **Yield** of 5 **Maize**, the blue farmer got 4 more **Maize**, achieving a total **Yield** of 6 **Maize**, the green farmer got 6 more **Maize**, achieving a total **Yield** of 11 **Maize** because the green farmer doesn't have an extra field then the 2 extra **Maize** must go to the extra seed compartment.

● **Phase 4: Selling phase:**

Only at the end of round 4, 8, 12.

The farmers decide who rolls the **Price dice** and the farmers calculate their **Profit** based on the total region production.

1. The total **Yield** from the region is calculated by adding the **Yield** from all farmers. The regional production is classified by the following criteria:

Number of players	Classification of Production		
	Poor	Optimal	Excessive
2	4 or less	5-21	22 or more
3	7 or less	8-32	33 or more
4	11 or less	11-43	44 or more

2. Based on the **Price dice** result, the **Profit** is calculated by multiplying the number of **Maize** in the field(s). Each farmer can choose how many **Maize** to sell. **Maize** in the extra seed compartment cannot be sold.

Dice Result	Maize Price based on the Production		
	Poor	Optimal	Excessive
0	$3,000	$6,000	$2,000
1	$5,000	$8,000	$4,000
2	$7,000	$10,000	$6,000
3	$9,000	$12,000	$8,000

After all farmers obtained their **Profit**, the victory points are calculated.

10

MAHIZ — RULEBOOK

> ### *Selling phase example:*
> *Based on the last example, the total regional production is 24 **Maize** which is in the Optimal classification. The **Price dice** result is 2, therefore the red farmer made a **Profit** of $50,000, the blue farmer made a **Profit** of $60,000, the green farmer made a **Profit** of $90,000 and the yellow farmer made a **Profit** of $20,000. The **Maize** located in the extra seed compartment cannot be sold. For the next four rounds the farmers now have what they have the money not spent from the budget saved and the **Profit** they made to keep or change their farm strategies.*

Scoring

Each farmer will move their farmers' marker in the scoring board accordingly to the victory points obtained. Victory points are awarded depending on the **Yield** and the **Profit**:

• Each **fully produced field** (e.g. 9 **Maize**) gives 10 victory points.
• The **Profit** made in the selling phase divided by $10,000

The victory crowns are earned when a farmer achieves more than 100 victory points so that the counting can be continued in the scoring board.

> ### *Scoring example:*
> *Based on the **Profit** and production in the previous examples the red farmer gets 5 victory points, the blue farmer gets 6 victory points and the yellow farmer gets 2 victory points, while the green farmer earned a total of 19 victory points, 10 for the full field and 9 for the **Profit**.*

End of the game

The game ends after 12 rounds. There is a selling phase at the end of the 12th round, which is followed by the last scoring. The farmer with the most victory points is the winner. In case of a tie, the farmer with most money wins. In case of a further tie, the farmers share the win. In case of bankruptcy, the farmer can negotiate a loan with the other farmers or end the game.

Description of Event Cards

All events are up for discussion and cooperation. Mutual advice and collective planning is encouraged.

11

RULEBOOK

MAHIZ

Weather Events

- **Drought!**: the **Rain dice** results of this round is educed by 3 drops.
Well level variation: remove 2 drops at the beginning of the round.

- **Flash Flood!**: if the **Rain dice** result of this round is 4 or more then the **Yield** is reduced by:

Rain	Yield
4	-1
5	-2
6	-3

Well level variation: add 2 drops at the beginning of the round.

- **Hot and Early Spring!**: the **Sun dice** result will be incremented by 2 drops.
Well level variation: remove 2 drops at the beginning of the round.

- **Cold and Late Winter!**: the **Yield** of each farmer is reduced by 2.
Well level variation: add 2 drops at the beginning of the round.

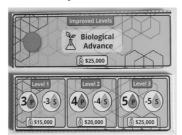- **No change**: no weather effects, only basic conditions based on the dice.

System Events

- **Technological Advance!**: there is an improvement available for the irrigation technologies, the farmers can buy this advance for $15,000 and get new levels of irrigation technologies that will stay for the rest of the game:

Well level variation: add 2 drops at the beginning of the round.

12

MAHIZ **RULEBOOK**

- **Biological Advance!** : there is an improvement available for the hybrid seed technologies, the farmers can buy this advance for $20,000 and get new levels of hybrid seed technologies that will stay for the rest of the game:

Well level variation: add 2 drops at the beginning of the round.

- **Environmental Policy**!: for this round only the technologies have an increased costs by +$1,000.

Well level variation: remove 2 drops at the beginning of the round.

- **Groundwater Policy!**: if the **Rain dice** result is less than 4, the farmers who have irrigation technologies installed decide to not use them in this round and earn $3,000 instantaneously. If the level of the **Well** is less than 2 then the farmers who used irrigation technologies have to pay a fine of $7,000.

Well level variation: remove 2 drops at the beginning of the round.

- **Organic products demand!**: the demand for regional non-genetically modified has increased , the farmers who have hybrid seed technologies installed decide to not use them in this round and earn $7,000 instantaneously.

Well level variation: add 2 drops at the beginning of the round.

- **Market equalizer!**: In the next selling phase, the farmers are ordered by production. The farmer with the most **Yield** can give 3 **Maize** to the farmer with the least **Yield** and money to secure a **Price dice** result of 2. For the rest of the farmers, the **Price** is set by rolling the **Price dice.**

Well level variation: no change.

13

RULEBOOK

- **Deficit irrigation!**: New type of irrigation technology is available. The farmers can buy this advance for $15,000 and get new levels of irrigation technologies that will stay for the rest of the game:
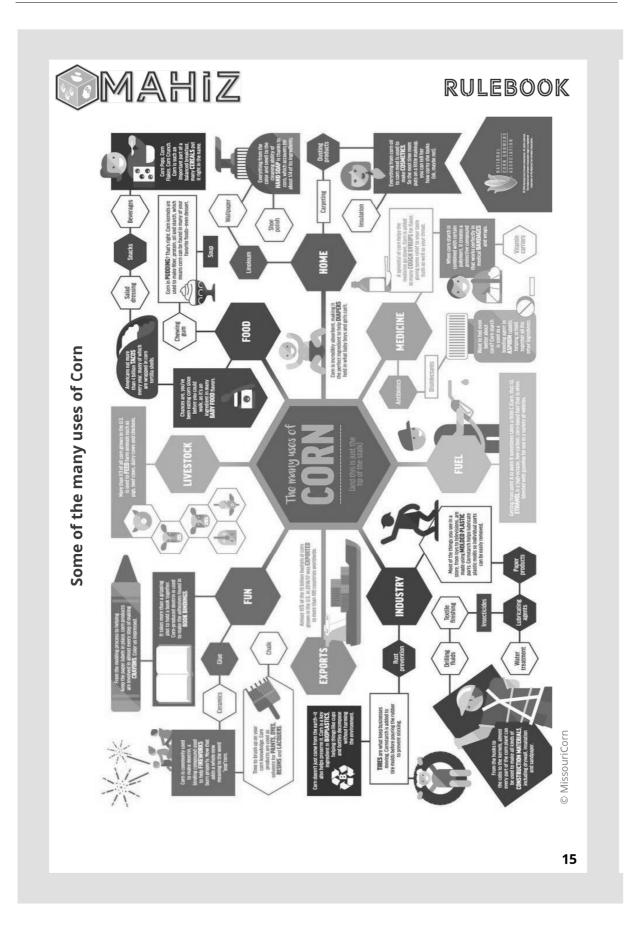

Well level variation: add 2 drops at the beginning of the round.

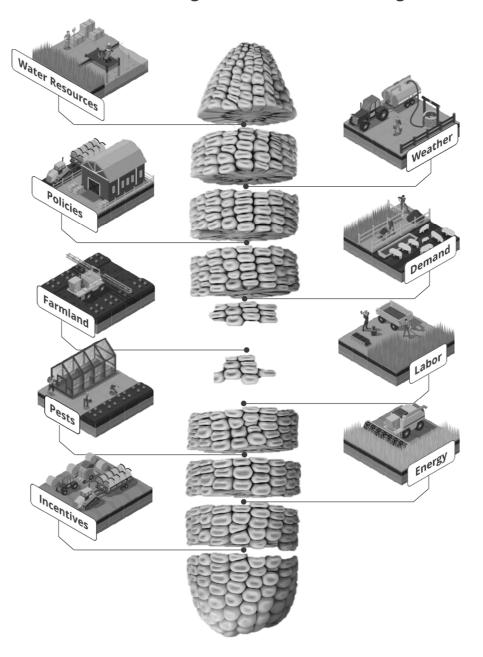- **No change**: no system effects, only basic conditions based on the dice.

Penalties and Loans

- **No production penalty**: In case a farmer doesn't produces any corn in the round, the farmer must play $2,000.

- **Bank Loan:** Farmers at any time can ask for money from the bank. The interest rate is a fixed one of 7% for each round.

14

Some of the many uses of Corn

Factors behind agricultural decision making.

Rulebook authors: Malena Orduña Alegría and Franziska Finster**.**

16

MAHIZ

Date:

FEEDBACK

Thanks for playing our serious board game! This form is to describe the experience you had playing the game and collect some data for our research project.

1. Did you find it:

Too short ☐	☐	☐	☐	☐	Too Long
Easy to Learn ☐	☐	☐	☐	☐	Confusing
Well Balanced ☐	☐	☐	☐	☐	Unbalanced
Meaningful Choices ☐	☐	☐	☐	☐	One Strategy
Enjoyable Theme ☐	☐	☐	☐	☐	Dull Theme
Fun ☐	☐	☐	☐	☐	Boring

2. Did you learn something new?

   Yes: ☐   No: ☐   Maybe: ☐

3. The **MoHub Framework** describe six theories on human decision-making in natural resource management models, based on their description found in the back of the page, please rank the following theories on scale of 1 to 6 with 1 being "very good description of my game strategy" and 6 being "not my game strategy".

   ☐ **Homo economicus**
   ☐ **Bounded Rationality**
   ☐ **Theory of Planned Behavior**
   ☐ **Habitual/ Reinforcement learning**
   ☐ **Descriptive Norm**
   ☐ **Prospect Theory**

4. Did you change strategies during the game?

   Yes: ☐   No: ☐   Maybe: ☐

Why and When?

5. Comments and Suggestions: (e.g. What did you like? What did you dislike? What would you change?)

Thank you so much for your time and thoughts!

MoHuB Framework for Mapping and Comparing Behavioural Theories

Theory	Description	Key assumptions
Homo Economicus	Rational choice theory.	• Self-interested utility maximization. • Goal-oriented. • Stable and transitive preferences. • Perfect knowledge. • Unlimited cognitive capacity for calculating outcomes of all possible behavioural options.
Bounded Rationality	Rationality is limited by available information and cognitive capacity.	• 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).
Theory of Planned Behavior	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 and their normative value. • 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).
Habitual/ Reinforcement learning	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.
Descriptive Norm	Social norms are the key element affecting decision-making. Descriptive norms: influence of perceiving what other people do 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.
Prospect Theory	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).