Imane El-Fartassi

Agent-based modelling of crop management

School of Water, Energy & Environment
Environment and Agrifood

PhD

Academic Year: 2020 - 2024

Supervisors:
Prof. Ron Corstanje
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

Academic Integrity Declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that knowingly submitting work in violation of the above statement will be considered by examiners as academic misconduct.

Contribution to jointly authored papers

This thesis includes both published papers and those submitted for publication. These papers are co-authored with multiple contributors; therefore, I use the plural pronoun "we" when referring to the collaborative work. In sections where the work is solely my own, I use the singular pronoun "I". I confirm that I am the lead author and I have made substantial contributions to each of the papers included. Detailed CRediT authorship contribution statements are provided at the end of each chapter.

Abstract

This study aims to explore the benefits of integrating Agent-Based Models (ABMs) of farmer behaviour with biophysical models to describe and understand the complex agroecological systems that influence decision-making in arid and semi-arid regions. Through a mixed-methods approach combining surveys, interviews, and ABM, the research provides insights into the complex dynamics shaping farmer behaviour and evaluates the potential impacts of various management strategies on agricultural sustainability. Initial online surveys across diverse agro-climatic zones in Morocco revealed that farmer decisions are influenced by environmental pressures, crop characteristics, and water availability. Follow-up in-depth interviews in the Al Haouz Basin highlighted institutional barriers like land tenure insecurity and bureaucratic processes as key constraints to adopting sustainable practices. The study integrates empirical data with Structural Equation Modelling and the Theory of Planned Behaviour to parameterize an ABM. This coupled behavioural-biophysical simulation captures feedback loops between environmental conditions and human decisions. Model simulations revealed potential unintended consequences of policies aimed at increasing productivity, such as increased soil salinization and land abandonment resulting from expanded groundwater access. Key contributions include advancing the understanding of temporal adaptation dynamics in agricultural systems under climate change and developing a novel methodological framework integrating qualitative and quantitative approaches for studying complex socio-ecological systems. By bridging social and natural sciences, this research establishes a comprehensive framework for addressing agricultural sustainability challenges in water-scarce regions.

Keywords:

Farmer decision-making, Sustainable agriculture, Adaptation, Structural Equation Modelling, Theory of Planned Behaviour, Water scarcity

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ABM	Agent-Based Modelling
PBC	Perceived Behavioural Control
SEM	Structural Equation Modelling
TPB	Theory of Planned Behaviour
DCMs	Discrete choice models

1 Introduction

1.1 General Introduction

Throughout Earth's history, ecosystem changes have primarily been driven by shifts in environmental conditions, climate, and complex interactions between biotic and abiotic factors at various spatial and temporal scales (Barnosky et al., 2012; Mori et al., 2018). These changes have shaped the evolution and distribution of life on Earth, resulting in the diverse array of ecosystems we see today (Blois et al., 2013). However, in recent decades, human activities have emerged as a dominant force driving ecosystem changes at an unprecedented rate and scale (Schipper et al., 2020; Steffen et al., 2015).

While natural forces acting on geological and biological processes were the primary drivers of ecosystem change for most of Earth's history, recent evidence suggests that human activities have become an equally significant driver (Chen et al., 2019; Ellis et al., 2021). The scale and speed of human-induced ecosystem alterations since the mid-20th century are unparalleled in human history (Zalasiewicz et al., 2021).

Recent advancements in remote sensing and modelling techniques have provided a more comprehensive understanding of the extent and consequences of land use and change on a global scale (Song et al., 2018; Toumasis et al., 2024). These studies have highlighted the significant impact of land management on ecosystem services, which include provisioning (e.g., food and fibre production), supporting (e.g., soil formation and nutrient cycling), regulating (e.g., climate and water regulation), and cultural services (e.g., recreational and aesthetic values) (Kirby et al., 2024; Power, 2010). Changes in land management practices can alter the capacity of ecosystems to provide these services, ultimately affecting human well-being (Newbold et al., 2015; Tsiafouli et al., 2015). Recent studies have emphasized the importance of improving our knowledge of the factors that shape landscape changes, to effectively engage with these drivers through land use planning and management and mitigate potential negative impacts (Meyfroidt et al., 2018; Verburg et al., 2015).

Global environmental challenges, such as climate change, biodiversity loss, and resource depletion, have heightened concerns about the vulnerability, adaptability, and sensitivity of both natural and social systems (Steffen et al., 2015). These challenges have been particularly relevant in the agricultural sector, as food production heavily relies on climatic conditions and ecosystem health (Ortiz-Bobea et al., 2021). Effective planning for agricultural land management has become increasingly complex and crucial for ensuring sustainable food production and ecosystem conservation.

Despite intensive research on land use observation, monitoring, and modelling (Pongratz et al., 2018; Verburg et al., 2019), a complete understanding of the underlying mechanisms driving human-environment interactions, such as feedbacks between social, economic, and ecological processes, remains elusive. This is largely due to the inherent complexity of coupled human and natural systems (Liu et al., 2021) and the cross-scale, non-linear processes involved in human-environment dynamics (D. Müller et al., 2014; Reyers et al., 2018). For example, in agricultural systems, the relationship between drought conditions and farming practices illustrates these complex dynamics. When farmers collectively respond to water scarcity by intensifying irrigation, their combined actions can alter groundwater availability and quality at the landscape scale. These environmental changes then influence future farming decisions, creating feedback loops between human choices and natural processes that operate across different temporal and spatial scales. The outcomes of these interactions are often difficult to predict due to their non-linear nature. The difficulty in decoding the complexity of human decision-making processes and incorporating them into modelling frameworks became increasingly recognised as a major limitation (Filatova et al., 2016; Schlüter, Orach, et al., 2019). Recent studies have increasingly acknowledged the significant influence of human activities—particularly the behavioural dynamics of individuals managing ecosystems—on landscape transformations. These studies have emphasised the importance of considering the role of individuals who actively manage ecosystems to gain a more holistic and nuanced understanding of the dynamics and drivers of ecosystem changes (Fischer et al., 2015; Lescourret et al., 2015).

The emergence of the human-environment system concept, which highlights the profound impact of human activities on the environment, signalled a paradigm shift in environmental studies (Fischer et al., 2015; Schlüter, Orach, et al., 2019). This new perspective moved the field beyond the traditional boundaries of pure and applied science towards the social sciences. However, observations of environmental change feedback on both nature and human societies suggested that both should be viewed as components of a “complex adaptive system” (Levin et al., 2013; Reyers et al., 2018). This led to the development of the socio-ecological systems approach, which portrays the constant, two-way interactions between humans and nature (Balvanera et al., 2017; Martín-López et al., 2017).

The integration of the human dimension into environmental studies has encountered practical challenges, particularly when considering the dynamics and feedbacks between human actions and ecological processes, highlighting the necessity for modelling approaches that capture these interactions (An, 2012). The most widely used framework draws its theoretical foundations from the rational choice theory (Schlüter et al., 2018). Rational Choice Theory is a framework that explains human behaviour by assuming individuals act rationally to maximise their preferences (Bridge, 2020). The basic assumptions of Rational Choice Theory are that individuals are homogeneous, have consistent preferences and act rationally to maximise their utility (Vanberg, 2016). However, the theory has faced criticism for its idealised and unrealistic assumptions.

While these assumptions provide analytical tractability and enable deductive reasoning, they disregard the heterogeneity of human societies and the limitations of human knowledge and cognition (Schlüter, Orach, et al., 2019). These simplifications can lead to inaccurate predictions and a limited understanding of the complex dynamics between human behaviour and the environment.

As a result, there have been calls for broader versions of rational choice theory that allow for a wider range of preferences and account for the formation and evolution of these preferences over time (Krstić, 2022).

Empirical evidence shows that individuals tend to conform to the choices of others in group decisions, leading to suboptimal outcomes (Dillenberger & Raymond, 2019) without necessarily following the same decision-making pathways (Linder et al., 2021). This shift has prompted the development of more nuanced and comprehensive theories and frameworks that go beyond traditional rational choice models. Recent studies have emphasised the importance of incorporating bounded rationality (Viale, 2020), heterogeneous decision-making (Schill et al., 2019), and social interactions in modelling human behaviour in environmental contexts (B. Müller et al., 2013; Schulze et al., 2017).

Bounded rationality, a concept introduced by Simon (1990) and further developed by Gigerenzer & Selten (2001), acknowledges that human decision-making is constrained by cognitive constraints, time, and available information. This theory suggests that individuals often rely on heuristics and simplified decision rules to make choices, rather than engaging in extensive deliberation and optimisation.

Studies have emphasised the importance of accounting for heterogeneous decision-making among individuals (Rathwell et al., 2015; Schill et al., 2019). People have diverse preferences, values, and experiences that shape their choices and actions. In addition to individual-level factors, people are embedded in social networks and social interactions can facilitate the spread of information, influence opinions, and lead to the emergence of collective behaviours (Groeneveld et al., 2017; B. Müller et al., 2013). With the rapid advancement of technology and global connectivity, these social networks are expanding and becoming increasingly interconnected, amplifying the importance of understanding social dynamics in decision-making processes. Thus, incorporating social dynamics into models of human behaviour enables a better understanding of how individuals' choices are shaped by their social environment and how collective action can emerge in response to environmental challenges.

These elements help explain the discrepancies between observed and predicted behaviour by accounting for the psychological constraints and cognitive limitations that influence human decision-making (Grayot, 2022; Müller-Hansen et al., 2017). Integrating bounded rationality and social interactions into models of human behaviour in environmental contexts can lead to more accurate predictions and effective interventions for sustainable resource management (Elsawah et al., 2020; Huber et al., 2018).

Dhami et al. (2019) and Gershman et al. (2015) challenged the traditional assumption that people make optimal choices based on rational deliberation. Instead, they argued that individuals often rely on simple heuristics, such as representativeness and loss aversion (Le Lec & Tarroux, 2020), to make satisfactory decisions while minimising cognitive effort. These heuristics, although efficient, can lead to systematic biases and suboptimal outcomes.

Recent research has further expanded on these ideas, exploring the role of cognitive biases, emotions, and social influences in shaping human decision-making in various contexts, including environmental and resource management (Elsawah et al., 2020; Müller-Hansen et al., 2017). For example, the affect heuristic, which describes the influence of emotional responses on judgment and decision-making, has been shown to play a significant role in shaping risk perceptions and environmental attitudes (Van Winsen et al., 2016).

Additionally, the concept of social norms has gained prominence in explaining individual behaviour in environmental contexts. Social norms refer to the shared expectations and rules that guide behaviour within a group or society. This concept can be further broken down into two types of norms: descriptive norms, which refer to perceptions of what most people do, and injunctive norms, which refer to perceptions of what people ought to do, have been shown to significantly influence pro-environmental behaviour and support for environmental policies (Farrow et al., 2017; Nyborg et al., 2016). When individuals perceive that engaging in pro-environmental behaviour is common and socially approved, they are more likely to adopt such behaviours themselves (Farrow et al., 2017; Robert B. Cialdini et al., 1990). This highlights the importance of considering social influences and the role of normative feedback in promoting sustainable practices.

Socio-psychological frameworks have placed greater emphasis on the complexity of human decision-making. For example, the Value-Belief-Norm theory proposed by Stern et al. (1999) and further elaborated by Stern (2000), has emerged as an influential framework for understanding the psychological and moral dimensions of human decision-making in environmental contexts. The Value-Belief-Norm theory posits that individuals' values, such as altruism and environmental concern, shape their beliefs about the consequences of environmental problems and their ability to reduce threats through their actions. These beliefs, in turn, activate personal norms or moral obligations to engage in pro-environmental behaviour. It suggests that individuals are more likely to engage in pro-environmental behaviour when they hold strong personal norms and believe that their actions can make a difference in addressing environmental issues.

Another influential socio-psychological framework is the Theory of Planned Behaviour (TPB), an extension of the Theory of Reasoned Action (Fishbein & Ajzen, 1975), which describes human behaviour as the product of an individual's *attitudes, subjective norms,* and *Perceived Behavioural Control (PBC). Attitudes* refer to an individual's positive or negative evaluations of performing a particular behaviour. *Subjective norms* describe the perceived social pressure to engage in or refrain from a behaviour, based on the expectations of significant others. *Perceived behavioural control* reflects an individual's belief in their ability to perform a given behaviour, considering factors such as resources, opportunities, and barriers. This framework has been widely applied in environmental psychology to understand and predict pro-environmental behaviour (Morren & Grinstein, 2021; Yuriev et al., 2020).

The TPB has also been extensively used to describe and understand farmer behaviour across various agricultural contexts. Recent studies have demonstrated its applicability in sustainable farming practices and disease management. For instance, Jowett et al. (2022) employed the TPB to examine factors driving farmers' adoption of sustainable pest management techniques. Their research also assessed how targeted engagement materials could influence attitudes and behaviours towards these practices. A study in Uganda found that farmers' *intention* to adopt agroforestry technologies was mainly driven by their evaluation of the benefits of shaded coffee *(attitude)* and beliefs about their own capability *(PBC)* (Buyinza et al., 2020). Similarly, Milne et al. (2018) used the TPB to frame farmers' and growers' decision-making processes. By conducting surveys at grower meetings, they gathered insights to improve management strategies for Huanglongbing, a destructive citrus disease. They aimed to enhance grower cooperation and participation in area-wide control programs by understanding the underlying factors influencing farmers' choices. While the TPB provides a robust theoretical framework for understanding farmer behaviour, researchers often seek to quantify the relative importance of various factors and validate the model's appropriateness in specific contexts. To address this need, Structural Equation Modelling (SEM), a powerful statistical technique, is widely used in conjunction with the TPB in social and behavioural research. It allows for the simultaneous analysis of relationships between multiple variables, including both observed and latent (unobserved) constructs, making it particularly suitable for examining the complex interactions within the TPB framework (Behjati et al., 2012). For instance, Wang et al. (2023) used SEM to model how farmers' *attitudes, subjective norms, and PBC* simultaneously influenced their intentions to adopt water-saving practices while accounting for the interrelationships between these psychological constructs. Similarly, the effect of water availability on crop revenue (Zewdie et al., 2019) was examined using SEM to account for the influence of multiple latent factors, such as economic constraints and farmer perceptions, which are difficult to measure directly., In the case and the adoption of low-carbon technologies adoption (Yang et al., 2022), SEM enabled the simultaneous analysis of how socioeconomic, psychological, and environmental factors interacted to influence decision-making, providing a more comprehensive understanding of adoption dynamics.

Despite the existence of behavioural models that move beyond basic assumptions, they have rarely been integrated into complex systems models (Cunniffe et al., 2015). This is due to the persistent disciplinary isolation of social and environmental sciences, which has challenged interdisciplinary research (Hertz & Schlüter, 2015; Milne et al., 2018), and the limited potential of modelling techniques used to model human-environment interactions to accommodate the complexity and diversity of human decision-making processes (Groeneveld et al., 2017; Guerrero et al., 2018). The integration of behavioural models into complex systems models has been further hindered by the lack of standardized protocols for coupling these models and the computational challenges associated with simulating large-scale, multi-agent systems (Dressler et al., 2019; Li et al., 2023).

Recent technological and computational advances have enabled the development of new methods that address these challenges and relax the simplified assumptions of traditional analytics. Process-based biophysical models have traditionally been used to simulate environmental systems by focusing on physical and biological processes such as water flow, soil dynamics, and crop growth (T. Foster et al., 2017; Letcher et al., 2013). However, these models often struggle to incorporate human decision-making processes. Economic models rely on rational choice theory to predict human behaviour (Bridge, 2020), yet they tend to oversimplify decision-making by assuming perfect rationality. System dynamics models are useful for representing feedback loops and time delays within coupled human-environment systems (Di Baldassarre et al., 2015; Noël & Cai, 2017), but they often assume homogeneous actors and lack spatial representation, which limits their capacity to model individual-level diversity. Integrated assessment models (IAMs) combine environmental, economic, and social components to evaluate policy impacts (Reidsma et al., 2018), though they frequently sacrifice depth of detail in favour of providing a broad overview of system interactions. Cellular automata models represent spatial processes through simple grid-based rules, making them well-suited for simulating urban growth or land-use change (Verburg et al., 2015). However, these models face challenges in incorporating complex human behaviour and institutional factors.

Hybrid approaches that integrate different modelling techniques are increasingly employed to address complex socio-ecological systems (Bulatewicz et al., 2010). These approaches combine strengths from various modelling paradigms to offer more comprehensive insights, but reconciling differing temporal and spatial scales presents a significant challenge. Each of these modelling approaches has specific strengths, but also inherent limitations when it comes to representing the complexity of human-environment interactions, highlighting the ongoing need for methodological advancements (Jakeman et al., 2016). One of the most promising approaches for future research in the field of human-environmental interactions is agent-based modelling (ABM) (Schlüter et al., 2018), particularly due to its ability to represent the heterogeneity and complexity of human cognitive processes (Murray-Rust et al., 2013). Agent-based models have been successfully applied to various domains, including plant disease epidemics and management (Milne et al., 2018), land-use change (Huber et al., 2018; Verburg et al., 2019), natural resource management (Lippe et al., 2019; Schulze et al., 2017), climate change adaptation (Zhang et al., 2024) and policy evaluation (Kremmydas et al., 2018), demonstrating their versatility and potential for integrating social and environmental systems.

Agent-based models are populated by autonomous, interacting entities called “agents” (Macal & North, 2013). These agents can represent a wide range of actors, from individual land managers (e.g., farmers) to higher-level entities in an organizational hierarchy (e.g., associations, organizations, countries). Each agent type is characterized by a distinct set of attributes that distinguish them from other agents in the model such as their goals, preferences, and decision-making processes (Huber et al., 2022). They operate based on behavioural rules that enable them to interact independently with other agents and their environment (Groeneveld et al., 2017; Huber et al., 2018; Schulze et al., 2017).

Various software tools and platforms have been developed to implement ABMs, each with different capabilities and features. In their comprehensive review, Abar et al. (2017) evaluated agent-based modelling and simulation tools, comparing their features, programming languages, usage difficulty, and application domains. They found that while some platforms are specifically designed for particular domains like social science or ecology, others offer more general-purpose functionality. The choice of modelling platform ultimately depends on factors such as the complexity of the intended behavioural rules to be implemented, the required level of programming expertise, and the specific needs of the research project.

These behavioural rules can be modelled using various approaches, each offering unique perspectives on agent interactions and decision-making processes. For instance, game theory principles can be incorporated to model strategic decision-making in competitive or cooperative scenarios (von Neumann & Morgenstern, 2007). This approach is particularly useful when modelling farmers' decisions in resource allocation or market participation. Opinion dynamics models, on the other hand, can be employed to simulate how agents' beliefs or opinions evolve through social interactions (Milne et al., 2020). This is especially relevant when studying the spread of agricultural innovations or the adoption of new farming practices within a community. Other modelling approaches include reinforcement learning, where agents learn from the outcomes of their past actions (Mnih et al., 2015). These diverse modelling techniques allow to capture the complexity of human behaviour in agricultural systems, from individual farmer choices to collective action dynamics.

Agent-based models can translate empirical data, often derived from social surveys and behavioural theories, into interactive, autonomous agents within a simulated environment (An, 2012; Groeneveld et al., 2017).

Agent-based models have emerged as a powerful tool for simulating complex systems, particularly in the context of human-environment interactions (Milne et al., 2020; Schwarzinger et al., 2013). They provide a testbed that allows the investigation of emergent, large-scale patterns or phenomena derived from self-organisation processes and interactions between systems (An et al., 2020; Filatova et al., 2013; Lippe et al., 2019). Agent-based models are constructed as computer simulations, where the rules governing the interactions and behaviours of individual agents are specified. These models then simulate the emergent behaviour as the ensemble of interactions. Such systems often exhibit emergent collective behaviours that differ from the individual actions of their constituent agents. The aggregate effects of these individual actions can have significant consequences but are not adequately accounted for in existing planning tools. To address this issue, there is an pressing need to incorporate an understanding of agents' decision-making processes into land-use and management tools, enabling decision-makers at various levels to develop more informed strategies for the future of agricultural land (Appel & Balmann, 2019; Dou et al., 2020; Huber et al., 2018).

While ABMs have shown great potential for simulating complex human-environment interactions and supporting policy analysis, there remains a gap in their application as operational tools for scenario analysis and the exploration of management strategies (Filatova et al., 2013; Groeneveld et al., 2017). Recent studies have highlighted the need for more policy-relevant ABMs that can effectively bridge the gap between scientific research and practical applications (Lippe et al., 2019; Verburg et al., 2016). To achieve this, models must be designed with stakeholder involvement and focus on addressing specific policy questions or management challenges (Elsawah et al., 2020; Voinov et al., 2016). Engaging decision-makers and other relevant actors in the model development process can help ensure that the model captures the key aspects of the system and produces outputs that are meaningful and actionable for policy and management purposes (Milne et al., 2020; Seidl, 2015).

The rural landscape is a typical example of human-environment interactions (Barton et al., 2016) as decisions related to land management are driven by human decision-making. It showcases the impact that human decision-making and land management practices can have on ecological systems (Meyfroidt et al., 2018).These decisions, which include choices about agricultural practices, resource use, and conservation efforts, have consequences for the structure, function, and sustainability of rural ecosystems (Fernández-Nogueira & Corbelle-Rico, 2020; Jepsen et al., 2015). Agent-based models have been increasingly applied to study land-use change and management in rural landscapes, providing insights into the complex interactions between individual decision-making, social networks, and environmental conditions (Miyasaka et al., 2017).

However, to fully realise the potential of ABMs in supporting sustainable land management and policy development in rural areas, further research is needed to address the challenges associated with model parametrisation, validation, and integration with other modelling approaches (Brown et al., 2017). This includes the development of methods for incorporating empirical data on human decision-making and behaviour into ABMs (Elsawah et al., 2015; Schlüter et al., 2018), as well as the integration of ABMs with other modelling tools, such as biophysical models, to provide a more comprehensive assessment of the trade-offs and synergies between different land-use scenarios (Milne et al., 2020; Plantinga, 2015; Synes et al., 2019).

1.2 Research Context

African rural ecosystems face unique challenges in balancing the growing demands of development and conservation. Climate change exacerbates these challenges, intensifying water scarcity and drought conditions, and threatening agriculture and food security in vulnerable developing nations (Serdeczny et al., 2017; Zougmoré et al., 2016). These impacts are particularly severe in arid and semi-arid regions, where a large proportion of the population depends on rainfed agriculture and is highly sensitive to changes in precipitation patterns and temperature extremes (Sultan & Gaetani, 2016).

As Africa's population grows rapidly, effective planning for sustainable agricultural land management becomes increasingly complex (Van Ittersum et al., 2016). As a result, traditional farming methods are progressively replaced by more intensive agricultural activities. This shift has led to the expansion of agricultural land, the adoption of high-yielding crops and varieties, the prevalence of irrigated monocultures, and the use of fertilizers, pesticides, and energy. However, limited knowledge regarding the appropriate use and timing of these inputs has exacerbated environmental impacts. These changes have profoundly impacted the environment, potentially inducing loss of natural habitats, species extinction, reduction in genetic diversity, soil erosion, and the scarcity and contamination of water resources. To address these challenges, integrated management frameworks that balance agricultural production goals with long-term resource sustainability are urgently needed (Mpandeli et al., 2018). Such frameworks should incorporate a systems perspective, considering the complex interactions between social, economic, and ecological factors that shape rural landscapes (Ramankutty et al., 2018; Searchinger et al., 2018).

Current land management planning approaches often lack the integration of socio-economic and socio-cultural information with biophysical information. This is particularly problematic when planning for agriculture, as farmers' decisions and behaviours have a substantial impact on land and water resource use across vast areas. The aggregate effects of these individual actions can have significant consequences but are not adequately accounted for in existing planning tools. To address this issue, it is imperative to incorporate an understanding of on-farm decision-making processes into land-use and management planning tools, enabling decision-makers at various levels to develop more informed strategies for sustainable management (Groeneveld et al., 2017).

Agent-based models offer a promising approach for integrating human decision-making into land management planning and policy analysis in African rural ecosystems. By simulating the interactions between individual farmers, their environment, and the broader socio-economic context, ABMs can provide insights into the emergent patterns of land management and resource management that arise from these complex dynamics (Berger et al., 2017; Troost & Berger, 2014). However, the application of ABMs in African contexts is still limited, and further research is needed into how to develop and adapt these models to the specific challenges and opportunities of these regions (Dobbie et al., 2018).

1.3 Research aim and objectives

This study aims to understand the implications of integrating ABMs of farmer behaviour with biophysical models and how this can be used to describe and understand complex agroecological systems that drive decisions in arid and semi-arid regions.

The objectives of this thesis are fourfold:

1) Characterize factors influencing farmers’ decision-making in Africa through an online survey with farming stakeholders and identify a case study for in-depth analysis and modelling.

2) In the selected case study area, gain an in-depth understanding of farmers' decision-making processes and the context in which they operate.

3) Build a coupled behavioural-biophysical simulation model that effectively describes the complex agroecological systems that drive decisions in arid and semi-arid regions.

4) Use the behavioural-biophysical simulation model to evaluate scenarios and make recommendations for improving agricultural sustainability in arid and semi-arid regions.

1.4 Methodological Approach

1.4.1 Geographical Context

Morocco is situated in the northwestern extremity of the African continent, bordered by the Mediterranean Sea and the Atlantic Ocean, with a diverse landscape ranging from coastal plains to mountains and desert regions (Figure 1-1). This geographical diversity is mirrored in its climate, which transitions from Mediterranean conditions along the coast to increasingly arid patterns inland and towards the south (Born et al., 2008).

A defining feature of Morocco's climate is its high variability, both inter-annually and intra-annually, with significant spatial differences in precipitation. Annual rainfall ranges from over 800 mm in the northern mountainous regions to less than 200 mm in the southern desert areas (Knippertz et al., 2003). This variability, coupled with varying evapotranspiration rates and soil characteristics, creates a mosaic of hydrological conditions across the country. Frequent drought periods pose significant challenges to water resource management, influencing agricultural water availability and management strategies in different regions (Jarlan et al., 2015). This variability, coupled with growing water demands from various sectors, has pushed Morocco below the water poverty threshold of 1,000 m^3/capita/year, highlighting the acute water scarcity issues faced by the country (Schyns & Hoekstra, 2014).

The agricultural sector, characterized by a blend of traditional and modern farming practices, contributes about 14% to the national GDP and employs about 40% of the workforce (World Bank, 2021). Cereals, particularly wheat and barley occupy nearly 60% of the cultivated area (MAPMDREF, 2020). Morocco is also known for its high-value horticultural crops, including citrus fruits, olives, and vegetables, which contribute to agricultural exports (OEC, 2023).

Irrigation is a critical component of Moroccan agriculture, while only about 18% of the cultivated area is irrigated, these lands account for 45% of the agricultural GDP and 75% of agricultural exports (Molle & Tanouti, 2017). The country’s water resources are under significant pressure, with agriculture consuming approximately 87% of the available freshwater (FAO AQUASTAT, 2023). This high dependency on irrigation, coupled with recurring droughts and increasing water scarcity, has led to the overexploitation of groundwater resources. It’s estimated that about 30% of aquifers are being extracted beyond their recharge capacity, leading to declining water tables and increasing salinity issues in some regions (Molle & Tanouti, 2017).

In response to these challenges, Morocco has various strategies to modernize its agricultural sector and improve water use efficiency. The Green Morocco Plan, launched in 2008 and succeeded by Generation Green 2020-2030, aims to increase agricultural productivity, enhance water use efficiency, and improve farmers' incomes (MAPMDREF, 2020). As part of these efforts, there has been a significant push towards adopting more efficient irrigation technologies, with drip irrigation systems now covering over 585,000 hectares, up from just 120,000 hectares in 2008 (MAPMDREF, 2020).

The country's geographical diversity of agro-ecological zones makes it a microcosm of various African agricultural landscapes. This diversity allows for the study of a wide range of agricultural systems and water management strategies within a single country. Morocco's experience with climate change impacts, particularly increasing aridity and rainfall variability, offers valuable lessons for adaptation strategies relevant to many African nations facing similar challenges (Schilling et al., 2020).

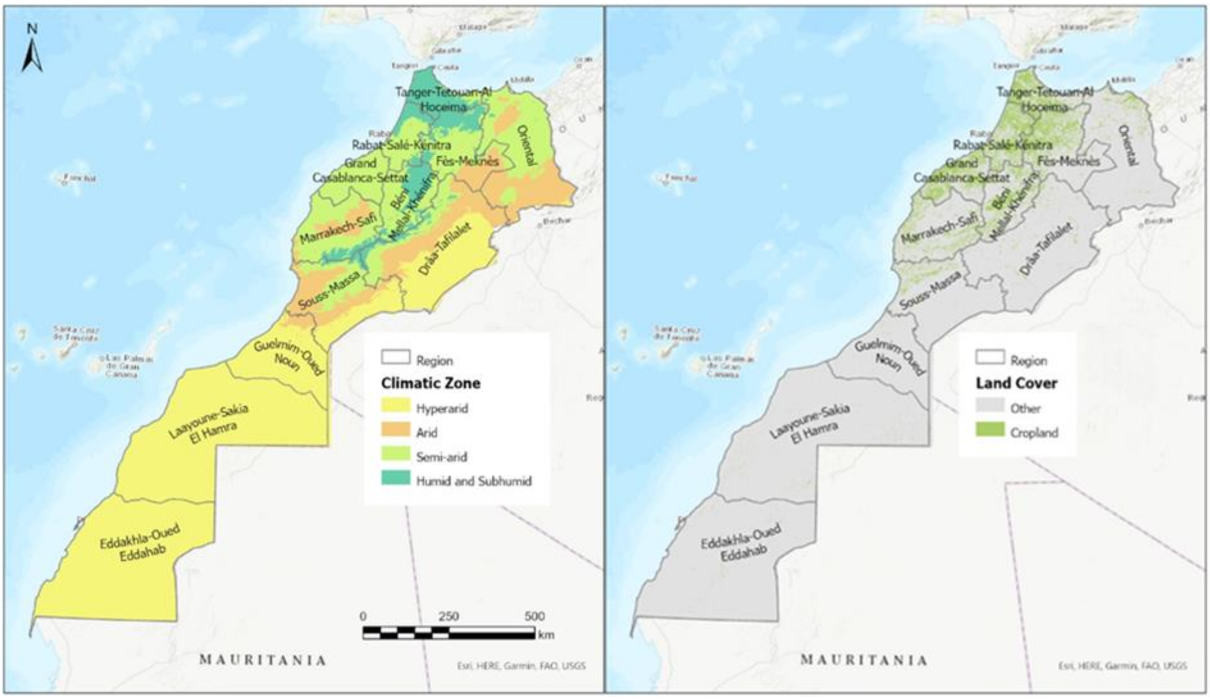

Figure 1-1 A map of Morocco showing administrative regions, climatic zones and cropland distribution.

1.4.2 Study Site

The research focused on the irrigated perimeter R3 (Figure 1-2). This area is located in Al Haouz plain, situated in the Tensift basin in Morocco, approximately 40 km to the east of Marrakech and covers an estimated area of 3800 km^2. The climate is semi-arid continental, with significant variations in rainfall both annually and within each year. On average, the region receives 250 mm of precipitation annually, with 70% of this amount falling during winter and spring. Evapotranspiration potential is high and can reach up to 1500 mm annually. Temperature extremes range from an average winter low of 4°C to an average summer high of 37°C. The soil composition in the area varies from clay to loam. The Haouz Agricultural Development Regional Office is the local agricultural office in charge of the management of irrigation water. This local authority oversees irrigation infrastructure and determines water allocation from dams based on preset schedules for each agricultural season. The water allocation is based on the dam water level and involves negotiations with farmers. Farmers having access to the dam water are organized in self-ruled associations called Agricultural Water Users Associations, which are formal organizations that partially enable them to manage and maintain their irrigation system.

In this area, field delineation was incomplete, so to characterize the study area more precisely, I undertook additional steps to delineate the agricultural parcels and gain a deeper understanding of the irrigation scheme organization. I used Very High-Resolution satellite imagery to segment the landscape into homogeneous areas based on several a priori attributes such as spectral reflectance, texture, and shape (Blaschke, 2010). This object-based image analysis approach allowed for a more accurate representation of field boundaries and land use patterns within the R3 perimeter (For more details, see supplementary data).

To gain a better understanding of local farming practices and challenges to sustainable agriculture, I conducted a participatory workshop with local farming stakeholders. This stakeholder engagement process provided insights into the social and operational aspects of water management in the area. The workshop facilitated the collection of local knowledge on irrigation practices, crop choices, and water allocation mechanisms (El Fartassi et al, 2024), which complemented our remote sensing-based parcel delineation.

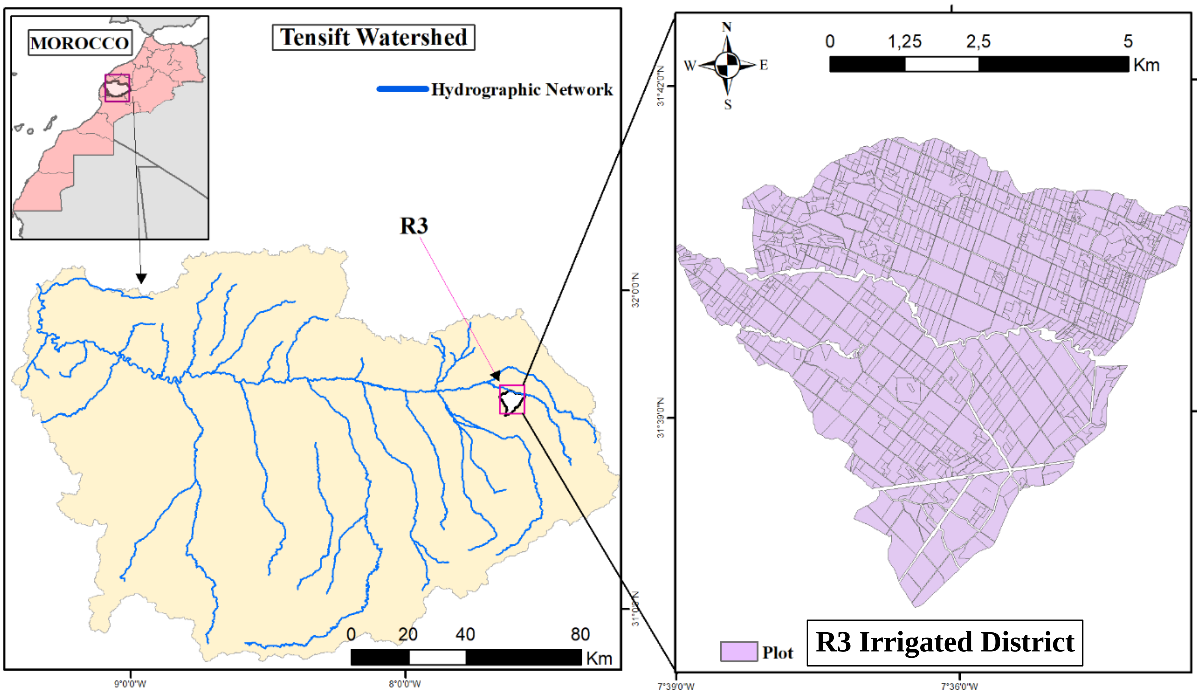

Figure 1-2 Location of the study area: R3 perimeter.

1.5 Thesis structure

This thesis is structured into seven chapters (Table 1-1). Insights gained at each stage of the research inform and drive the subsequent work, creating a cohesive and progressive narrative. While the chapters build upon one another, each one is a standalone chapter designed to be read independently.

The first chapter serves as a general introduction, providing an overview of the research topic and the thesis's objectives.

In chapter two, I investigated the factors influencing farmer decision-making. Data was gathered through online surveys distributed to farming advisors and professionals who worked across the contrasting environments of Morocco.

Based on the findings of chapter two, a case study was selected on improving the sustainability of irrigation for deeper investigation and modelling. I conducted extensive in-depth interviews with 70 farmers in the Al Haouz Basin, Morocco. The aim was to explore farmer decision-making within the context of a climate change-induced water stress environment. We gathered insights into the motivations for irrigation choices, focusing on farming systems exposed to increasing climate risks.

In Chapter Three, I developed a set of quantitative methodological approaches to analyse the data collected. Inductive coding was used to evaluate qualitative responses, and data was further analysed to determine how farm size and tenure influenced decision-making. An integrated modelling approach based on a combination of TPB and SEM was used to interpret drivers of irrigation management strategy.

We then developed an agent-based modelling framework. Chapter Four presents an application of the conceptual framework that integrates behavioural and biophysical models to investigate shared irrigation water management. The behavioural models simulated farmers' decisions about their water irrigation sources (dam or underground) and whether to continue cultivating in the face of drought. The behavioural model was parameterised based on the factors identified in Chapters Two and Three. The biophysical model component quantified the impact of water availability and irrigation source sources on soil salinity accumulation and its effects on crop productivity. In this chapter, we explored the complex trade-offs between short-term gains and long-term sustainability, emphasising the need for holistic water governance policies that balance individual and collective interests.

Chapter Five discusses the main findings of this thesis and also discusses avenues for future research.

Chapter Six provides conclusions from the entire body of work presented in this thesis.

My PhD project was part of an OCP-funded programme aimed at developing a GIS-based modelling framework (GIS-MF) that integrates process-based models and data to describe agriculture and its impacts on semi-arid landscapes in Morocco. The GIS-MF can be used to explore trade-offs associated with production and other ecosystem services and evaluate the resilience of farming systems within this landscape.

While the broader project focuses on integrating models with remote sensing data to predict agricultural impacts, my PhD specifically addresses the human dimension. I developed an ABM framework to simulate farmers' decision-making processes, complementing the project's technical and biophysical aspects. This integration provides a broad view of how individual farmers' choices collectively influence agricultural landscape dynamics.

Table 1-1 Thesis structure and status of paper submissions.

Chapter Link	Paper	Title	Journal	Status
1		Thesis Introduction		
0	1	Evidence of Collaborative Opportunities to Ensure Long-Term Sustainability in African Farming	Journal of Cleaner Production	Journal of Cleaner Production Volume 392 15 March 2023 Received 3 August 2022; Received in revised form 24 December 2022; Accepted 22 January 2023
3	2	Adaptations in Agricultural Water Management in Arid Regions: Modelling Farmer Behaviour and Cooperation on Irrigation Sustainability	Agricultural Water Management	Under Review
0	3	An Agent-Based Model of Farmer Decision Making: Application to Shared Water Resources in Arid and Semi-Arid Regions	Agricultural Water Management	Under Review
0		General Discussion		
6		Conclusions		

2 Evidence of collaborative opportunities to ensure long-term sustainability in African farming

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2.1 Abstract

Farmers face the challenge of increasing production to feed a growing population and support livelihoods, whilst also improving the sustainability and resilience of cropping systems. Understanding the key factors that influence farming management practices is crucial for determining farmers' adaptive capacity and willingness to engage in cooperative strategies. To that end, we investigated management practices that farmers adopt and the factors underlying farmers' decision-making. We also aimed to identify the constraints that impede the adoption of strategies perceived to increase farming resilience and to explore how the acceleration of technology adoption through cooperation could ensure the long-term sustainability of farming. Surveys were distributed to farming advisors and professionals who worked across the contrasting environments of Morocco. We used descriptive statistics and analysis by log-linear modelling to predict the importance of factors influencing farmers' decision-making. The results show that influencing factors tended to cluster around environmental pressures, crop characteristics and water availability with social drivers evidently playing a lesser role. Subsidies were also found to be an important factor in decision-making. Farming advisors generally believed that collaborative networks are likely to facilitate the adoption of sustainable agricultural practices. We conclude that farmers need both economic incentives and technical support to enhance their

adaptive capacity as this can lessen the socioeconomic vulnerability inherent in arid and semi-arid regions.

2.2 Highlights

- Farmers' behaviour is impacted by constraints rather than opportunities.
- Environmental pressures, crop characteristics and water availability shape farmer behaviour.
- Influencing factors are generalizable but adaptation is context-specific.
- Subsidies and cooperation enhance sustainable farming practices uptake.
- Economic incentives and technical support strengthen farmers' adaptive capacity.

2.3 Introduction

Across Africa, and in particular, in arid and semi-arid regions, farmers face the daunting challenge of increasing production to feed a growing population and support livelihoods, whilst also improving the sustainability and resilience of cropping systems (Tittonell & Giller, 2013). Environmental, economic, and social factors (e.g., land tenure, or cultural practices) influence and constrain farming practices (Poteete & Ostrom, 2004). These factors also drive or constrain the adoption of new practices (Kassie et al., 2015). Therefore, to determine opportunities for the adoption of more sustainable practices it is important to understand the factors influencing farm management decisions.

Africa is particularly affected by climate change and the negative impacts are predicted to be substantial compared with other regions of the world (Diffenbaugh & Giorgi, 2012). Climate warming has adverse implications for agricultural production. Land suitability for agricultural use, yield potential along with growing season length and dates are expected to be compromised, particularly in semi-arid and arid regions (Ramos & Kahla, 2009). The continuous and significant warming temperatures mean that drought conditions are likely to be aggravated leading to an increased risk of crop losses (Cook et al., 2016). Climate change is not only an environmental challenge but also a development issue as its adverse effects disproportionately poorer countries where economies mostly rely on agriculture (Wheeler & von Braun, 2013). These problems are exacerbated by the fact that farmers from arid and semi-arid African developing countries have little capacity to adapt (Faiyetole & Adesina, 2017). However, how farmers are likely to adapt to the pressures associated with climate change has not been fully characterised.

Moreover, in response to current and expected water scarcity and to keep abreast of increasing food demands, there is a drive to expand the irrigated land where possible (Mashnik et al., 2017). Current agricultural intensification has resulted in unsustainable water withdrawal exceeding the regenerative capacity of the water table (Hamed et al., 2018), and intensive large-scale irrigation has led to increased soil salinity (Van Weert et al., 2009). Water shortage and soil salinity are not the only environmental challenges faced by farmers in arid and semi-arid regions of Africa, they also face risks of erosion and soil fertility decline resulting in depleted carbon sequestration (Lal, 2012). These biophysical pressures are exacerbated by the deficient and inadequate application of nutrients impoverishing the already depleted African soils (Bationo, 2009).

In arid areas where there is water scarcity, and the extent of fertile land is limited, population pressure and the limited extent of fertile lands due to urbanization have contributed to the steady increase in agricultural intensification. Optimising land use is necessary and requires efficient use of fertilizers. Although the agrochemical industries are designing products based on appropriate application rates for optimum crop growth, there are still environmental and economic concerns related to agricultural inputs (Ryan et al., 2012). With rising global energy costs and associated increases in fertilizer costs, fertilizer use for smallholder farmers is becoming prohibitively expensive. These factors are also likely to impact farmer decision-making to varying extents.

Current agricultural methods rely on accelerated agricultural production to meet global food demand. Climate change is already affecting food security. Yet, many of the techniques that farmers adopt to increase productivity have a negative impact on sustainability. Unsustainable land management and poorly implemented intensification can have unintended consequences (Masson-Delmotte et al., 2019). It can cause biodiversity loss, and soil salinization, and threaten the viability of farmers' livelihoods. These challenges and other drivers exacerbate the vulnerability of arid and semi-arid ecosystems and heighten the socio-economic inequity between farmers. Considering that Africa faces increased risks and limited benefits associated with climate change, most opportunities lie in optimizing the continent’s response to future climate shocks.

There are key areas of management that can be targeted to develop sustainable solutions and mitigate the negative impacts of climate change. For example, the introduction of agroforestry provides potential means to cope with the adverse effects of changing climate conditions through microclimate improvement. It plays a crucial role in enhancing the ecosystem's resilience through extended soil moisture retention and increased rainfall utilization (Mbow et al., 2014). Agroforestry contributes to buffering atmospheric accumulation of greenhouse gases and enhancing carbon sequestration, thus, strengthening smallholder farming systems' resilience (Verchot et al., 2007). Sustainable intensification provides the opportunity to achieve food security, act as a climate mitigation strategy, and present an alternative to the over-use of agrochemicals. A further example is no-till farming, an integrated agroecological approach to enhance ecosystem resilience and increase adaptation and mitigation (Corbeels et al., 2014). Compared with conventional tillage practices such as ploughing, no-till farming has the potential to reduce nutrient losses by wind and water erosion, increase soil carbon sequestration and in the longer term improve crop productivity. Finally, low-efficiency surface irrigation systems can be replaced by drip irrigation technology which meets crop water needs and improves water-use efficiency. These systems also hold the potential to incorporate nutrients thereby improving the efficiency of fertilizers. These agricultural management practices help deliver multiple ecosystem services mitigating climate change through soil organic carbon sequestration and reducing the intensity of water scarcity inherent in landscapes across African countries.

Understanding the key factors influencing farmers’ decision-making is crucial for ongoing dialogues for climate mitigation and sustainability strategies (Wood et al., 2014). Wood et al. (2014) assessed and compared factors associated with reported changes in agricultural practices by smallholder farmers across multiple regions. They found economic factors, participation in local institutions and access to weather information were significantly associated with changing farming practices. Perez et al. (2015) examined the conditions in East and West Africa that underlie the vulnerability of farmers and their resilience to climate change. They identified population growth, commercialization of the economy, and natural resource use policies as key drivers of change with better yields and profit being the most commonly reported drivers. These studies do not explicitly explore opportunities to increase sustainability, nor do they attempt to directly link influencing factors to specific management choices. Our research aims to address these gaps by focusing on how identified factors can be leveraged to foster sustainable farming practices. Specifically, I investigate how these factors can drive specific management decisions, ultimately contributing to a more targeted approach for sustainability interventions.

In this study, we focused on Morocco given that its widely varying climates are representative of the diversified agroclimatic zones found across a wide range of arid and semi-arid African countries. In addition, climate change is expected to have a greater negative impact on Morocco relative to other African countries given the high reliance of the country’s economy on rain-fed agriculture (Schilling et al., 2012). This makes Morocco an ideal model representative of the climatic pressures that African countries are experiencing or are expected to experience.

This study aims to identify and describe opportunities to enhance the sustainability of farming practices by investigating the key factors underlying farmers’ decision-making and willingness to cooperate. We set out to explore crop management practices that farmers adopt in combination with the key factors underlying farmers’ decision-making. We identify the constraints that impede the adoption of strategies perceived to be more sustainable to explore how the acceleration of technology adoption through cooperation could benefit farmers and the environment. Our analysis contributes to a better understanding of the opportunities and constraints affecting the sustainability of farming in arid and semi-semi regions.

2.4 Materials and Methods

2.4.1 Study Context

The agricultural sector is a key national priority for Morocco given its contribution to the Gross Domestic Product (GDP): of 13% (MAPMDREF, 2018). Similar to other developing countries, farming is the prime employer and provides a living for 73.7% of the active rural population in Morocco. The Utilised Agricultural Land (UAA) is estimated to be 8.7 Mha, with croplands largely focused on the north of the country (Figure 1-2b). Cereals account for 59% of the UAA although they only contribute to 18% of the overall value of agricultural production. In contrast, horticulture with only 3% of the UAA, contributes to 21% of the overall agricultural production. According to the *De Martonne* aridity index, (which has been used to assess the aridity trends in several semi-arid and arid regions across Africa (Kenawy et al., 2016; Muhire & Ahmed, 2016)), there are four distinct climatic zones in Morocco (Figure 2-1a). These range from humid and subhumid to hyperarid (Mokhtari et al., 2013). Morocco receives approximately 29 billion m^3 of rainfall per year, out of which 69% is considered to have hydraulic potential that can be mobilised. The distribution of UAA is 81% rain-fed lands, 9% Large-scale hydraulics, 4% small and medium-scale hydraulics and 6% private irrigation scheme (MAPMDREF, 2018).

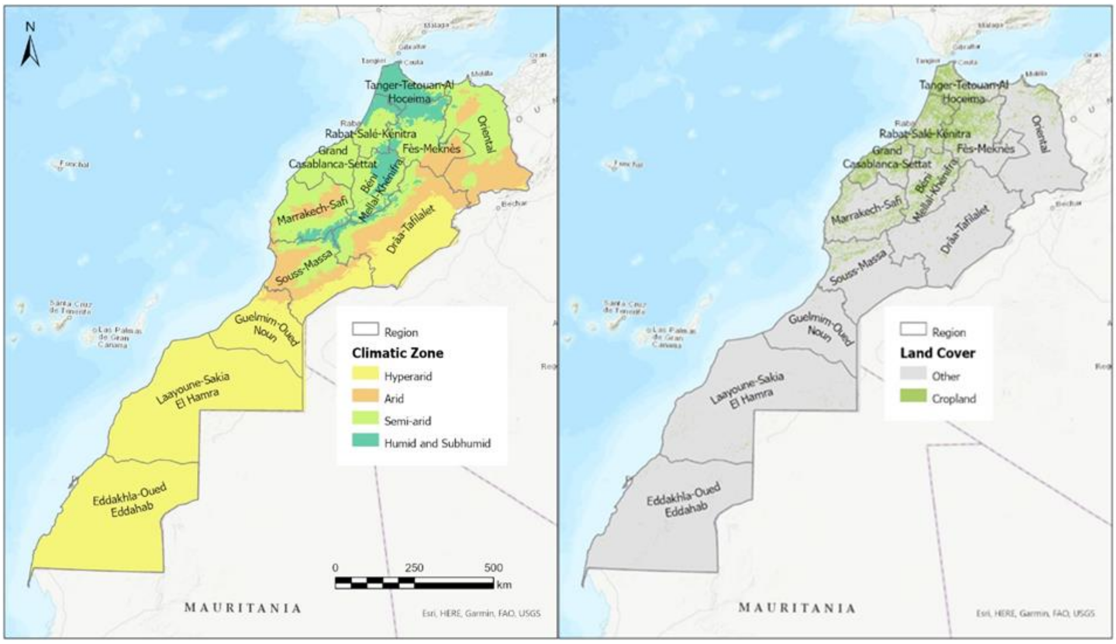

Figure 2-1 A map of Morocco delineated according to administrative regions showing (a) climatic zones based on the De Martonne aridity index and (b) the distribution of cropland.

2.4.2 Survey design and dissemination

The majority of farmers in Morocco are either illiterate or do not have internet access. In addition, there are very few online farmer networks through which to disseminate a survey. Hence, we aimed our survey at farming advisors from across Morocco. This allowed data to be gathered over a wide area enabling us to assess the generalizability of our results across contrasting environments.

The survey consisted of semi-structured questions on farming advisors' perceptions of different agricultural management practices in Morocco. We asked their perceptions about the factors that motivate the decisions of farmers in relation to crop management and posed questions about opportunities to improve the environmental sustainability of farming.

The survey structure was defined with reference to (Campbell et al., 2017). The questions were organised into five sections (Table 2-1 and 8B.1). Section 1 was about the general background of the respondents who assigned themselves to one of four "professional" groups. These were (1) "agronomist" which included government scientists, engineers, and technicians; (2) "agronomist developer" which included agronomists in charge of promoting products and technologies related to agriculture; (3) "agronomist consultant" refers to self-employed or employees in private companies or institutions that convey and recommend progressive agronomic and cultural practices to their growers, and (4) "agronomist advisors" refers to state farm extension agents working closely with farmers assisting them to solve problems in crop production. This question acted as a screener question to ensure we collected data from the target stakeholder group. The following sections were: i) Crop choices; ii) Tillage; iii) Irrigation and iv) Fertilizer management.

We surveyed farming advisors, including agronomists who represent and work closely with multiple farms. These agronomists were selected because they have in-depth knowledge of the farming practices within their regions, gained through direct interactions with farmers. To identify which crop, irrigation type, and other agricultural practices are most common, the agronomists relied on their extensive field experience, interactions with farmers, and access to agricultural data. Their expertise allowed them to provide informed responses based on their cumulative observations across different farms they worked with. This approach ensured that the data gathered was reflective of the general practices and trends across various farming communities, rather than isolated individual practices.

We first investigated the current management practices that farmers undertake. For tillage and irrigation, we asked respondents to rank a set of agricultural practices from most to least common. For fertilizer practices, we posed a multiple-choice question and allowed respondents to select the most common practice. We note that the analogous questions about which crops farmers grow were not asked. Instead, we obtained this information from regional crop statistics (MAPMDREF, 2018).

We asked the respondents to identify the key factors that influence farmers' decisions. The respondents were requested to rank the options provided using a 3-scale point (Not important, moderately important, and very important). To mitigate the risk of failing to satisfy the assumptions of multi-way contingency table analyses (expected cell counts of less than 5) we opted for a 3-point scale.

Thereafter, we asked the respondents if they noticed any behavioural persistence or slow adoption of innovative practices. Finally, we asked their opinion on whether the acceleration of technology adoption would benefit through cooperation between farmers. A summary of the survey is given in Table 2-1. The survey was piloted with a group of 15 agronomists and changes were made accordingly.

Table 2-1 A summary of sections 2 –- 4 of the survey questions.

Management Practices	**Section 2: Crop Choices**	**Section 3: Tillage**	**Section 3: Irrigation**	**Section 4: Fertilizer Management**
Management Preferences	Literature	Q 3.1: Rank the following tillage systems (conventional, reduced and no-tillage) according to how commonly they are adopted in your area.	Q 4.1: Rank the following irrigation systems (drip irrigation, surface irrigation, sprinkler irrigation, and rain-fed lands) according to how commonly they are adopted in your area.	Q 5.1: In your area, what type of fertilizer (organic fertilizers only, predominance of organic fertilizers and limited use of chemical fertilizers, equal use of both organic and chemical fertilizers, and predominance of chemical fertilizers and lower use of organic fertilizers) do farmers use the most?
Factors affecting farm management choices **(see 8B.3 for the list of factors)**	Q 2.1: To what extent do the following factors influence the choice of crops?	Q 3.2: To what extent do the following factors influence the choice of (i) conventional tillage, (ii) reduced tillage and (iii) No-tillage?	Q 4.2: To what extent do the following factors lead farmers to adopt (i) surface irrigation in your area (ii) drip irrigation in your area and (iii) sprinkler irrigation in your area?	Question 5.2: To what extent do the following factors influence the use of (i) chemical fertilizers and (ii) organic fertilizers?
Behavioural persistence, change or adaptation	Q 2.2: Have you noticed any behavioural persistence or slow adoption of agroforestry? Yes or No. If yes expand, if not, why do you think so? Text entry.	Q 3.3: Have you noticed any behavioural persistence or slow adoption of no-tillage practice? Yes or No. If yes expand, if not, why do you think so?	Q 4.3: In your area, how do farmers adapt to water shortages and other weather conditions?	Question 5.3: How can you describe changes in the use of fertilizers? For the list of options given in the survey see supplementary data. Question 5.4: To what extent do the following factors influence change in fertilizer use? For the list of factors given in the survey see supplementary data.
Cooperation patterns	Q 2.3: In your opinion, are there opportunities to improve agroforestry adoption through collaboration networks or co-creation plans? Yes or No. If yes expand, if not, why do you think so?	Q3.4: Are there opportunities to improve tillage practices through collaboration networks or co-creation plans? Yes or No. If yes expand, if not, why do you think so?	Q 4.4: In your opinion, are there opportunities to improve water management through collaboration networks or co-creation plans? Yes or No. If yes expand, if not, why do you think so?	Question 5.5: In your opinion, are there opportunities to improve fertilizer practices through collaboration networks or co-creation plans? Yes or No. If yes expand, if not, why do you think so?

The survey was created and hosted using Qualtrics (Qualtrics, Provo, UT), which is a web-based survey platform. An anonymous survey link was generated and disseminated through social media groups associated with agronomy using LinkedIn, Facebook, and Gmail, from June 2020 to January 2021. To ensure no duplicate entries, we asked respondents to fill in basic personal details (B.1.1). We allowed the respondents to stop in mid-survey and resume later where they left off. The responses in progress were retained for up to two weeks after the respondents started the survey. Respondents were able to review and change their responses up to the point they submitted them. Before data analysis, the data collected were anonymized and the respondent's IP address served as the unique ID in our database. Participation in the survey was voluntary, all questions were optional, and no incentive was offered for completing it. Prior to the data collection, the survey was submitted for ethical approval through Cranfield University's research ethics approval system.

2.3 Methods of analysis

Respondents were asked to record the administrative region of Morocco in which they worked but for statistical purposes, we aggregated responses across climatic zones based on the *De Martonne aridity* index (Figure 2-1). The zones used in our classification were "subhumid to humid", "semi-arid and subhumid to humid", "semi-arid" and "arid to hyperarid" (Table B-1 & Table_ B-2).

To analyse the data, we first tested to see if management preferences varied significantly according to climatic zones using a Pearson χ^2 test. Under the null hypothesis, the responses are independent of the climatic zone, and so the same distribution of responses is expected for each climatic zone. Where no significant difference in management preference was found, data were subsequently pooled across administrative zones of Morocco for further analysis, where differences were significant, we analysed data accounting for the climatic zones.

For questions about ranking management practice, we tabulated responses with ranks as the rows and practice types as the columns pooled across climatic zones. We tested to see if the ranking was significant compared with that expected from random allocation using the Friedman test (Friedman, 1937). The mean rank was also calculated. To assess the differences between the fertilizer regimes, we conducted a Pearson χ^2 test.

For the questions about what influences farmers' choices of management, we presented the results in contingency tables in which the rows are responses to the questions and the columns are the factors affecting the choice of management. The contingency table for Q 3.2 is given as an example (Table 2-2). The χ^2 test (described above) is appropriate where the data can be expressed in a two-way table, but for more complex tables log-linear modelling offers a suitable extension allowing one to partition out the effects due to individual variables (Chagumaira et al., 2021; Welham et al., 2014). In this case, the null hypothesis is that there is no interaction between management type and importance or influencing factor and importance. Therefore, we started with a baseline model that represents the null hypothesis. This model included the main effect of the response classifying factor (Importance) and the interaction involving the potential explanatory factors (Management type * Influencing factors). For example, in the case of Question 3.2 for tillage, the base model was given by:

Number of responses = Tillage type * Influencing factor + Importance

We then examined the interactions between the explanatory factors and responses by sequentially adding them to the model and testing to see whether including interactions between Importance and each Factor (Influencing factor and Management practice) significantly explained the variation in the data (Figure 2-2). Having identified the most appropriate models, tables of predictions were produced and plotted. These predictions are estimated mean values, formed on the scale of the linear predictor presented on the log-linear scale.

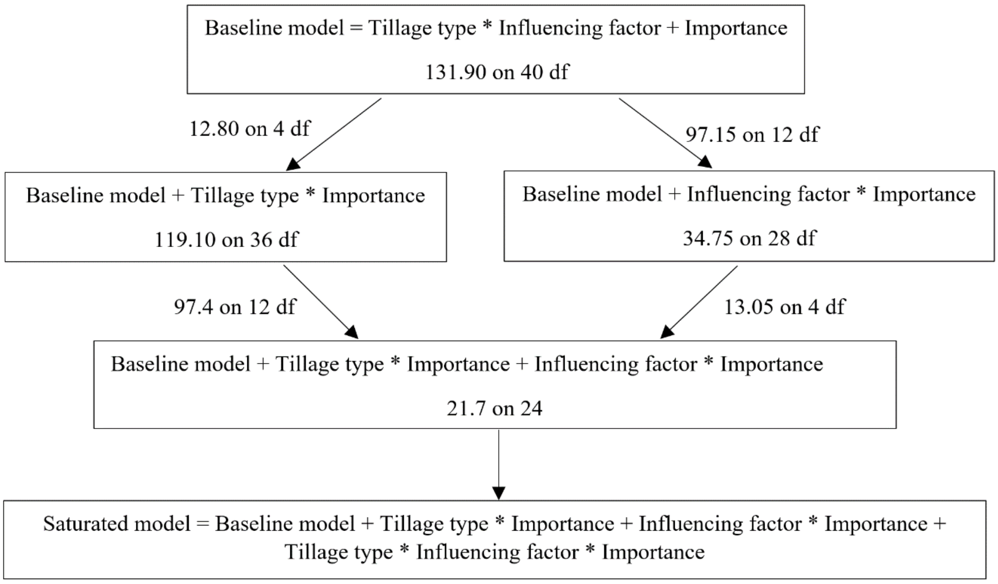

Figure 2-2 A network diagram illustrating the log-linear model's sequential fitting for contingency tables analysis. The base model describes the null hypothesis that there are no interactions between the response classifying factor (importance) and the potential explanatory factors. Interactions are sequentially added, and models and tested to see if the deviance reduces significantly. The order of fitting the interaction terms influences the change in deviance because the model is not orthogonal.

To explore the influence of various factors on crop choice (Q2.1) we adopted a similar approach to the above, but in this case including the climatic zone within our log-linear model as the climatic zone was found to be significant in crop choice. In this case, we used the relative proportion of responses since the factors were aggregated in broad-scale factors except for water availability (Figure 2-2). For the irrigation systems, the factors “Capacity and readiness to invest” and “Subsidies and grants” are not relevant to surface irrigation. Therefore, we fitted one log-linear model excluding these factors across all three irrigation systems and a second including these factors for drip and sprinkler irrigation. The qualitative data, particularly questions related to the behavioural persistence, change or adaptation toward the adoption of new farming technologies, in addition to cooperation among farmers, were coded and categorised following the identification of similar themes. Subsequently, we assessed whether the willingness or unwillingness to adopt sustainable farming techniques varied depending on the climatic zones by performing a χ^2 permutation test for the “crop choices” and “tillage” sections.

Table 2-2 The full contingency table showing how many individuals selected a response to Q3.2: “To what extent do the following factors influence the choice of (i) conventional tillage, (ii) reduced tillage and (iii) no-tillage?” The Influencing factors are A) so soil and land characteristics; B) crop characteristics; C) water availability; D) Subsidies and grants; E) farm size; F) passed down through the generations; G) phytosanitary management.

	Factors for choosing tillage systems																				
	Conventional Tillage							**Reduced Tillage**							**No-tillage**						
Influencing factors	A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
Not important	10	6	15	23	20	13	21	11	8	14	30	23	28	22	16	11	16	27	23	27	23
Moderately important	28	32	34	38	32	30	36	29	38	28	34	31	25	39	23	25	20	31	31	35	31
Very important	48	47	38	23	33	41	29	41	36	40	18	28	27	21	44	46	47	25	27	21	27

2.5 Results

2.5.1 Responses recorded per region.

Table 2-3 shows the number of useable responses per climatic zone for each section of the survey.

Table 2-3 Useable responses recorded per climatic zone.

Climatic zones	Tillage	Crop choices	Fertilizer	Irrigation
Subhumid to humid	4	5	5	4
Semi-arid and subhumid to humid	32	27	16	24
Semi-arid	20	23	14	17
Arid to hyperarid	12	15	10	12
Respondents who did not identify with a region	25	6	2	4
Total	93	76	47	61

2.5.2 Contextual Questions

2.5.2.1 Crop Choices

The distribution of the surface areas of crop types varies significantly between climatic zones (χ^2=1415.22, $p < 0.001$), indicating a significant effect of the climatic zone on crop choices. All zones are dominated by cereals, with olive trees making up the next largest proportion of crop areas except for the arid-hyperarid zone where citrus, almond and date palm trees showed a slight dominance over olive trees (Table_ B-3 & Table_ B-4).

2.5.2.2 Tillage

The results from the χ^2 test showed no evidence to suggest that the ranking of tillage practice varied according to climatic zone (conventional tillage: $p = 0.563$, reduced tillage: $p = 0.405$ and no-tillage $p = 0.531$, (Table_ B-5, Table_ B-6 & Table_ B-7). Conventional tillage was ranked most common by the majority of respondents (Table_ B-8). The mean ranks obtained for conventional, reduced and no-tillage are 1.169, 2.253 and 2.554, respectively, where the smaller the value the more common the tillage type.

2.5.2.3 Irrigation

The results from the χ^2 test showed no evidence to suggest that the rankings of the irrigation systems varied according to climatic zone (drip irrigation p = 0.735, surface irrigation p = 0.246, sprinkler irrigation p = 0.237 and rainfed lands p = 0.792, (Table_ B-9, Table_ B-10, Table_ B-11 & Table_ B-12).

Drip irrigation was ranked most common by just over half of the respondents (p < 0.001, Table_B-13). The mean ranks obtained for drip irrigation, rainfed lands, surface and sprinkler irrigation were: 2, 2.359, 2.533 and 3.109, respectively.

2.5.2.4 Fertilizer Management

There were no significant differences in dominant fertilizer type according to climatic zone (p=0.932, Table_ B-14). There is a preponderance of "Predominance of chemical and lower use of organic fertilizers" (29 responses) and fewer counts of "Organic fertilizers only" (2 responses) (p<0.001, Expected values = 11.25).

2.5.3 Factors Affecting Farm Management Choices

2.5.3.1 Crop Choices

As our results showed significant differences in the distribution of crops according to climatic zones, we examined the effect of the climatic zone on the factors affecting crop choices. We first considered the broad scale factors which are "crop characteristics", "farm size and facilities", and "water availability" as well as "environmental", "economic", and "social" factors (Figure 2-3, Table_ B-15). Second, we examined the sub-factors of each set (Figure_ B-1, Table_ B-16, Table_ B-17, Table_ B-18, Table_ B-19 and Table_ B-20).

The accumulated analysis of deviance in Table 2-4 shows that there were no significant interactions between the climatic zones and the levels of importance on crop choice. On the other hand, the interaction between factors and importance was significant (p<0.001) implying that some factors are more important than others in influencing the choice of crops.

Table 2-4 Accumulated analysis of deviance for crop choice including the independent variables climatic zone and factors, factors, and importance and associated two-way interactions.

Change	**d.f.**	**deviance**	**mean deviance**	**deviance ratio**	**approx chi pr**
Climatic zones	3	168.77	56.26	56.26	<.001
Factors	5	0.00	0.00	0.00	*
Climatic zones.Factors	15	0.11	0.01	0.01	1
Importance	2	145.99	73.00	73.00	<.001
Climatic zones.Importance	6	4.25	0.71	0.71	0.643
Factors.Importance	**10**	**76.24**	**7.62**	**7.62**	**<.001**
Residual	30	28.35	0.95		
Total	71	423.72	5.97		

The prediction model shows that “water availability” was considered the most important factor influencing farmers’ decision-making about crop choice (Figure 2-3). The respondents believe that farmers are almost equally sensitive to the “environmental factors” and “crop characteristics” and that the “economic factors”, “farm size and facilities” and “social factors” are less important.

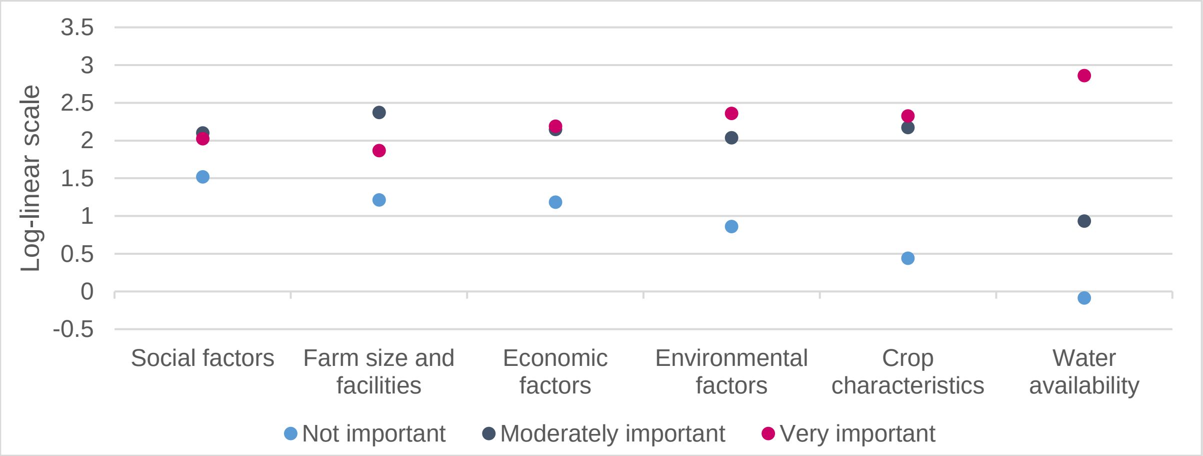

Figure 2-3 Predictions from the log-linear model of the importance of influencing factors on crop preferences. Where the points are tight or coincide, there was no strong consensus among those surveyed.

Regarding the “Economic factors”, the benefit from “subsidies and grants”, the “labour availability”, in addition to the “profitability”, are expected to influence crop selection (Pearson χ^2, p<0.001, Figure_ B-1, Table_ B-17). Amongst the “environmental factors”, the “climate” and “water availability” are the most important factors in this category (Pearson χ^2, $p < 0.001$, Figure_ B-1**,** Table_ B-16). For the social factor, the farming advisors deemed “the prior experience with the crop” as very important (Pearson χ^2, $p < 0.001$, Figure_ B-1**,** Table_ B-18). Regarding “crop characteristics”, “high yield” is considered the key determinant of crop selection (Pearson $\boldsymbol{\chi^2}$, $p < 0.001$, Figure_ B-1**,** Table_ B-19). The Pearson $\boldsymbol{\chi^2}$ shows no significant differences between the factors within the “farm size and facilities” ($p=0.131$, Figure_ B-1**,** Table_ B-20).

2.5.3.2 Tillage

Significant interactions existed between the tillage systems, the levels of importance, and the factors and importance (Table_ B-21). The effect of factors is twice the effect of tillage systems. This means that there is a significant interaction between importance and tillage systems and that some factors are significantly more important in influencing the adoption of a particular tillage system than others.

The prediction model shows that “water availability”, “soil and land characteristics” and “crop characteristics” are shown to be important drivers of choice for all tillage systems (Figure 2-4, Figure_ B-2**,** Table_ B-22**,** Table_ B-23 & Table_ B-24).

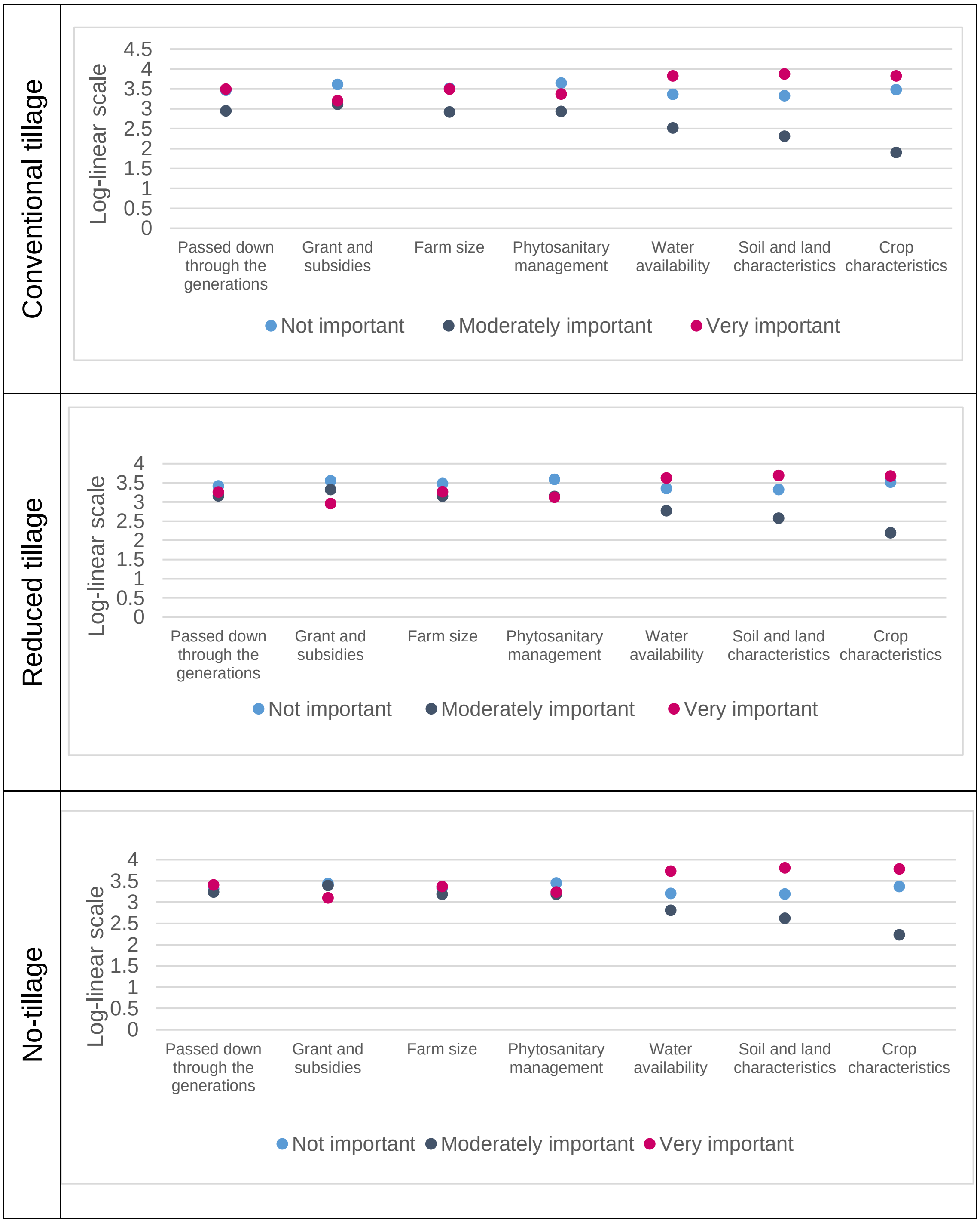

Figure 2-4 Predictions from the log-linear model of the importance of influencing factors on the adoption of conventional tillage, reduced tillage, and no-tillage. Where the points are tight or coincide, there was no strong consensus among those surveyed.

2.5.3.3 Irrigation

We found significant interactions between irrigation systems and the importance of influencing factors as well as significant differences between factors. Differences in response across irrigation systems were more substantial than differences across factors (Table_ B-25 & Table_ B-26). The predictions in Figure 2-5 highlight that across all systems “crop characteristics” and “water availability” are the most important factors for irrigation. This is particularly true for surface irrigation (Figure_ B-3, Table_ B-27). Notably, “labour availability” is less important for surface and sprinkler irrigation. “Climate” and “soil and land characteristics” are least commonly reported as very important for sprinkler irrigation (Figure_ B-3, Table_ B-29). “Profitability”, “capacity and readiness to invest” and “subsidies and grants” were deemed very important for drip irrigation by a large proportion of respondents (Figure_ B-3, Table_ B-28).

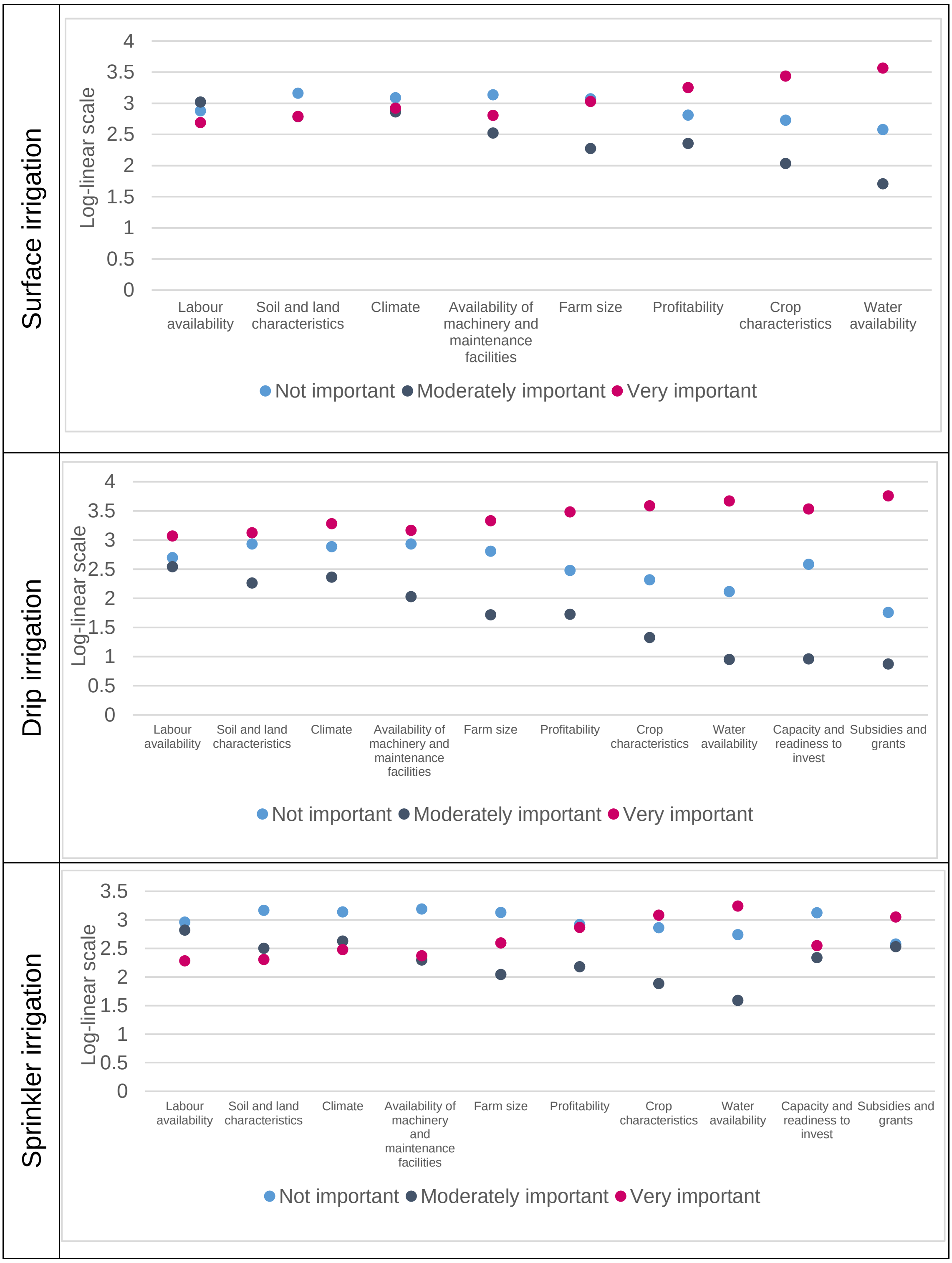

Figure 2-5 Predictions from the log-linear model of the importance of influencing factors on the adoption of surface, drip and sprinkler irrigation. Where the points are tight or coincide, there was no strong consensus among those surveyed.

For both drip and sprinkler irrigation, the benefit from "grand and subsidies" along with "capacity and readiness to invest" are recurrently ranked as very important (Figure 2-5).

2.5.3.4 Fertilizer Management

The accumulated analysis of deviance showed no significant interaction between fertilizer types and importance ranking and so we pooled across fertilizer types for our predictions (Table_ B-30). These show that achieving a "high yield" and "profitability" are key factors driving the use of fertilizers (Figure 2-6, Figure_ B-4, Table_ B-31 & Table_ B-32).

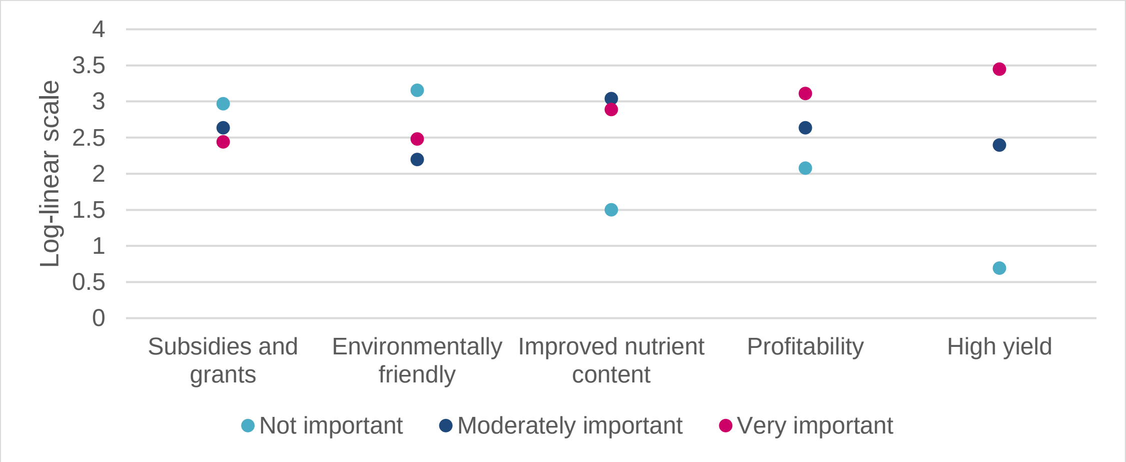

Figure 2-6 Predictions from the log-linear model of the importance of influencing factors on the adoption of chemical and organic fertilizers.

2.5.4 Behavioural persistence, change or adaptation toward the adoption of new farming technologies

2.5.4.1 Crop Choice: Agroforestry

There was no significant effect of the climatic zone on the perceived willingness of farmers to adopt agroforestry (Q 2.3, p = 0.114, Table_ B-33). When pooled across the climatic zone, just over 33% of respondents noted a reluctance of farmers to adopt agroforestry. This unwillingness was attributed to the low profitability and the delayed profit compared to intensive agriculture (11 out of 17 qualitative responses). The results also suggest that farmers prefer income-generating crops, are unwilling to adapt, and have a strong propensity to intensify production systems (6 out of 17 qualitative responses).

2.5.4.2 Tillage

Just over 45% of respondents noted a reluctance of farmers to adopt no-tillage. There was a significant effect of the climatic zone on the perceived willingness of farmers to adopt no-tillage systems (Q 3.3, $p = 0.05$), with a pronounced reluctance in the “Humid and Subhumid” and “Semi-arid / Humid and Subhumid” climatic zones compared to the other ones.

According to the results, lack of information on benefits (11 out of 38 qualitative responses) and the reluctance of farmers to adopt new practices (9 out of 38 qualitative responses) are the factors impeding no-tillage adoption. Farmers believe that no-tillage will hinder the growth and development of the crop and cause a decrease in crop productivity. In addition, no-tillage requires adequate equipment that may not be available (6 out of 38 qualitative responses).

2.5.4.3 Irrigation

In the “humid and subhumid” zone, farmers are not affected by water shortages and no contingency strategy is anticipated to face severe drought. For other regions, the adaptation strategies adopted were grouped into three categories: sustainable adaptation, unsustainable adaptation and forced adaptation.

Sustainable adaptation included the use of drought-resistant plants and varieties (9 out of 21 qualitative responses), adoption of drip-irrigation (6 out of 21 qualitative responses), adoption of new cultivation methods (3 out of 21 qualitative responses) such as no-tillage, construction of water accumulation basins (2 out of 21 qualitative responses) and transhumance (3 out of 21 qualitative responses) where intensive agriculture is not practised. Unsustainable practices such as the overexploitation of groundwater (3 out of 11 qualitative responses) coupled with deepening wells and drilling boreholes (8 out of 11 qualitative responses) are adopted by farmers to cover the deficit in crop water needs. According to the survey, forced adaptation translates mainly into the reduction in the area farmed (6 out of 12 qualitative responses), conversion to rain-fed crops (3 out of 12 qualitative responses) and reduction of irrigation frequency (3 out of 12 qualitative responses). Another coping strategy reported was seawater desalination (2 out of 12 qualitative responses).

2.5.4.4 Fertilizer Management

Differences in the importance of factors driving the uptake of chemical fertilizer were significant (p<0.001, Figure 2-7), with “Profitability”, “high yield” and “improved nutrient content” perceived to be the main factors driving the change toward greater use of chemical fertilizer coupled with organic amendments (Figure 2-7, Table_ B-34). According to the survey study, farmers recognize the role of mineral fertilizers as a supplement to the soil's nutrient stocks, which can be rapidly absorbed by crops.

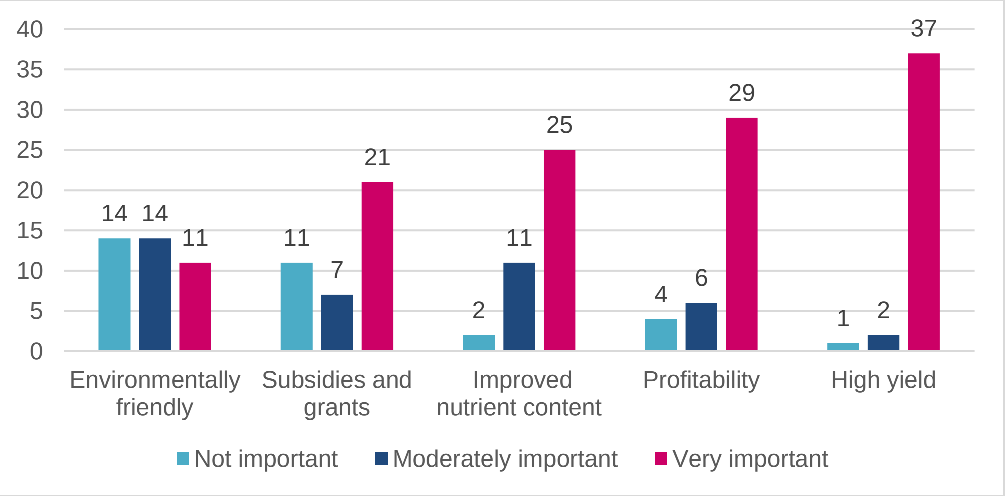

Figure 2-7 Factors affecting the change in the use of fertilizers

2.5.5 Farmer's willingness to adopt sustainable farming practices

2.5.5.1 Crop Choices

The survey revealed that 60% of respondents believe that agroforestry take-up could be improved through collaboration networks. Our respondents suggested that agroforestry adoption and management should be based on a participatory approach, supported by policymakers, associations, and governmental organizations (7 out of 25 qualitative responses). They also suggested the creation of cooperatives and associations to promote agroforestry and carry out field demonstration platforms and farmer field schools as a capacity-building strategy (7 out of 25 qualitative responses) to demonstrate the profitability and associated benefits of agroforestry (9 out of 25 qualitative responses).

2.5.5.2 Tillage

Approximately, 75% of respondents believe that the adoption of no-tillage could be increased through collaboration networks. It was stated that without consolidating the efforts of the various farming advisors via a collaborative approach, the adoption of no-tillage will remain meagre and have little impact, hence the prominent role of a participatory approach for no-tillage implementation (5 out of 45 qualitative responses). Respondents mentioned that farmers will adopt no-till practices if they see positive results in field conditions that are similar to their own. They also suggested organizing farmer field schools and workshops for farmers to demonstrate the long-term benefits associated with no-tillage (18 out of 45 qualitative responses). It was suggested that farmers could be organized into cooperatives (14 out of 45 qualitative responses) and credits could be facilitated for the purchasing of shared equipment (8 out of 45 qualitative responses).

2.5.5.3 Irrigation

Approximately, 80% of respondents believed that water management can be improved through collaboration. According to the results, several approaches could be adopted such as capacity-building training (9 out of 31 qualitative responses), land fragmentation correction (2 out of 31 qualitative responses), participatory management of water resources (2 out of 31 qualitative responses) and crop coordination (1 out of 31 qualitative responses). Respondents mentioned technical solutions such as the improvement of irrigation systems by fostering the implementation of drip irrigation (9 out of 31 qualitative responses), water treatment such as desalination and sewage treatment (4 out of 31 qualitative responses) as well as the construction of dams (1 out of 31 qualitative responses) in addition to grants and subsidies (3 out of 31 qualitative responses).

2.5.5.4 Fertilizer Management

Of those surveyed, 78% believed that fertilizer management could be improved through collaboration. Respondents suggested the implementation of capacity-building training and the participatory management of fertilizer use (9 out of 14 qualitative responses). Technical solutions (fertilizers based on soil analysis, 2 out of 14 qualitative responses) are perceived as an important component of sustainable fertilizer use (2 out of 14 qualitative responses).

2.6 Discussion

Our study set out to evaluate the potential for African farmers to adopt sustainable farming practices and contribute to the emerging literature on ways to operationalize cooperation-mitigation strategies (Döring, 2020; Perez et al., 2015). Our approach was to identify and describe the current practices adopted by farmers, the key factors that influence these and determine obstacles to the adoption of practices that are considered more sustainable. In our analysis, the key influencing factors tended to cluster around environmental pressures, crop characteristics and water availability. In contrast, social factors were identified but showed less significant influence on the decision-making process in this context.

2.6.1 Crop choice: influences and constraints on the adoption of sustainable practice

Our analysis shows that to assess the suitability of crops for specific agro-climatic zones in Africa, it is important to account for water availability, environmental factors, and crop characteristics (Figure 2-3, Table_ B-15). Local ecosystems have implications for crop adaptability and adoption by growers. Smallholder farmers’ productivity often depends on rainfed farming (Mitchell et al., 2006). Increasing yield potential, drought, and heat tolerance of commonly grown crops, such as Groundnut (*Arachis hypogaea* L.), can benefit farmer livelihoods (Singh et al., 2014). Moreover, short growth cycles of cereals such as

Millet (*Panicum miliaceum* L.) and Sorghum (*Sorghum bicolor* (L.) *Moench*) have also shown potential adaptation to climatic variations (Kouressy et al., 2008; Sultan et al., 2014).

Small-scale mixed cropping and livestock systems are reported to be the best strategy to become more environmentally sustainable and resilient to future climate shocks (Nhemachena et al., 2010). Drawing from Toujgani et al. (2021), agroforestry, beyond its ecological role as a sustainable intensification solution can help to generate additional income in marginalized land testifying to its socio-economic importance. However, our findings highlight that 33% of farmers are reluctant to adopt agroforestry due to their propensity to intensify production systems, perceived low profitability or delayed profit of agroforestry (Table_B-33). The adoption of a farmer-centric approach can overcome those constraints through technical assistance provided by extension services.

Subsidizing investment costs could also hasten farmers' agroforestry adoption as this would alleviate issues related to the delay in profitability. Since smallholder farmers are labour-constrained, agroforestry offers the opportunity to spread the demand for labour across the growing season. That is if farmers diversified their production, harvest periods will occur at more spaced-out times.

In addition, the type of tenure inherited from the protectorate period and post-independence in North African countries between the forester (representative or owner of the tree where it is) and the farmers who consider that they must have full control of their exploitation, pose a serious threat to the adoption of agroforestry. Raising awareness of land appropriation reform can influence farmers to opt for agroforestry as a mitigation solution to climate change. The respondents of our study provide useful insights into the role of a participatory approach in the development and management of agroforestry. It constitutes a sustainable farming model for smallholder farmers who can expand their market opportunities and convert marginalized lands into more productive ones.

2.6.2 Tillage choice: influences and constraints on the adoption of sustainable practice

The adoption of specific tillage systems was reported to be most impacted by soil and land characteristics, crop characteristics and water availability (Figure 2-4, Figure_ B-2, Table_ B-22, Table_ B-23 & Table_ B-24). These results are consistent with the findings of Bonzanigo et al. (2016) who indicated that the environmental constraints (i.e., soil and climate), in addition to rotations, crop characteristics, and residue availability are the key factors in determining tillage choice.

The results also suggest that farmers are not inclined to transition from conventional tillage to no-tillage; up to 45% of respondents noted a reluctance of farmers to adopt no-tillage. Several limitations hinder this transition, the most frequently cited are the lack of information on benefits, the reluctance of farmers to adopt new practices, the lack of appropriate equipment and the perception of yield loss.

To improve the no-tillage adoption rate, policymakers need to consider the limiting conditions to its adoption and tailor policies according to different farmers' typologies since smallholder farmers are generally more vulnerable to climate change. No-tillage cropping systems have been shown to offer many benefits to soils and grain production (Grandy et al., 2006). It has the potential to reduce soil, organic carbon, and nutrient loss erosion. Moreover, its effectiveness with respect to erosion control is high in arid and semi-arid regions given the expected increase in rainfall intensity events responsible for accentuating the erosion rate in those areas (Martínez-Mena et al., 2020). Furthermore, enhanced cover crops and incorporation of plant residues into the soil nutrient and organic carbon recycling can lead to improved soil conditions and increased water retention capacity.

The results highlight that the reluctance to adopt no-tillage is more pronounced in the “Humid and Subhumid” and “Semi-arid / Humid and Subhumid” climatic zones compared to the other ones. The drought is especially acute in arid zones and no-tillage has the potential to reduce the soil evaporation rate. This explains the willingness of farmers to adopt no-tillage in drought areas compared to less impacted regions.

To improve the no-tillage adoption rate, farming advisors need to address barriers related to crop type, water management, and equipment availability through collective action. Additionally, they should work to effectively communicate the long-term benefits of no-tillage practices, such as improved soil health and resource efficiency, which can help overcome initial perceptions of potential challenges. While there is often a perception that no-tillage results in yield reductions, research has shown that these effects may not be as significant in the long term. A global meta-analysis by Pittelkow et al. (2015) found that, although no-tillage can lead to initial yield declines, these effects diminish over time, with yields eventually reaching levels comparable to conventional tillage, particularly when combined with good nutrient management practices. Another study by (Cui et al., 2024) Reveals showed that no-tillage, especially when combined with crop residue return and crop rotation, can mitigate yield losses and even enhance soil organic carbon sequestration. These studies indicate that the yield losses associated with no-tillage are often temporary and can be mitigated through appropriate management practices, suggesting that the perception of persistent yield loss may not fully reflect the longer-term potential benefits of no-tillage.

Designing customised policies that respect farmers’ typologies is essential given the socio-economic constraints of smallholder farmers struggling to meet their immediate needs (Baudron et al., 2015; Branca et al., 2021). Therefore, allowing farmers to gradually adopt no-tillage components and progressively improve them along with the technical support of extension services, can demonstrate the full potential of this practice as part of a socio-technical network (Yigezu et al., 2021).

2.6.3 Irrigation choice influences and constraints on the adoption of sustainable practice

Although it is complex to predict the behaviour of individual farmers, it is possible to identify factors that tend to influence their decision-making in predictable ways. Overall drip irrigation was ranked the most common form of irrigation by the respondents closely followed by rainfed. This somewhat contradicts national statistics which suggest that by area rainfed agriculture is dominant (MAPMDREF, 2018). Additionally, a large proportion of the irrigated area (63%) is still under surface irrigation (MEF, 2019). This contradiction could stem from the fact that, while rainfed agriculture is dominant by area, irrigated areas may contribute disproportionately to overall production, resulting in respondents perceiving irrigation methods, such as drip irrigation, as more common. Alternatively, it could reflect an ongoing trend toward the adoption of drip irrigation, particularly among farmers who have access to subsidies and the capacity to invest. The adoption of drip irrigation was substantially more influenced by subsidies and grants and the capacity to invest than other forms of irrigation (Figure 2-5, Table_ B-25 & Table_ B-26). This demonstrated the link between the adoption of drip irrigation and subsidies.

The latter provoked an adjustment in farmers’ behaviour shifting from surface irrigation to drip irrigation. Designed incentives targeting farmers at different scales enhanced the uptake of drip irrigation in Morocco. This policy enabled technology transfer, but we do not know if farmers' behaviour will readjust when the incentives no longer prevail.

The change in the irrigation methods (incentivised by subsidies) has induced a change in plantation choice. The influence of the politico-economic factors on crop selection is illustrated in Theriault & Smale (2021), where the Malian government launched a fertilizer subsidy program to enhance fertilizer use by targeting strategic crops. This incentive played a crucial role in shifting the agricultural landscape and orienting crop diversity, reinforcing farmers' predisposition to align with the national strategies of governments.

We can infer from the results some indicators associated with resilience when it comes to water conservation practices. Thus, farmers may adopt sustainable, unsustainable, and/or forced adaptation strategies to reduce drought impact. These differences across adaptation patterns can lead to a positive and resilient outcome such as the use of drought-resistant plants and varieties or can lead to an unviable agricultural practice for example the overexploitation of groundwater. This demonstrates that adaptation strategies vary across farmers and are context-specific. Consequently, policies should be designed to meet the adaptation capacities of farmers and drive them towards sustainable solutions and away from ones that are not viable in the long term.

2.6.4 Fertilizer choice influences and constraints on the adoption of sustainable practice

Innovative approaches need to consider profitability. As revealed by our findings, chemical fertilizers are the predominant form used by farmers and this is driven by the desire to achieve a high-income yield (Figure 2-6, Figure_ B-4, Table_ B-31 & Table_ B-32). Our study shows a perceived shift towards greater use of inorganic fertilizers coupled with organic amendments and is driven by achieving a high yield and profitability (Figure 2-7, Table_ B-34). Higher incomes mean that farmers will be able to achieve higher potential returns on fertilizer investment. In Sub-Saharan Africa, the average fertilizer consumption is estimated at 22.5kg of nutrients per hectare of arable land, much lower than the world's average fertilizer consumption (estimated at 135kg/ha) making African agriculture one of the least productive worldwide.

Additionally, African countries display a heterogeneous trend in fertilizer adoption, due to the limited accessibility, investment costs, and unawareness of the benefits associated with fertilizers (Sheahan & Barrett, 2014). For example, Malawi and Nigeria record the highest number of chemical fertilizer applications and Uganda record the fewest. In Malawi and Nigeria, the use of fertilizers is endorsed by a governmental subsidy programme (Holden, 2018), testifying to the role of policies in shaping farmer decision-making. However, such programmes must be deployed carefully. The over-use of fertilizers and pesticides in agricultural production can cause disturbance in the ecosystem and lead to increased risk of environmental pollution, namely, surface and groundwater quality (Sutton et al., 2019), soil pollution (Huang & Jin, 2008), air quality (Walling & Vaneeckhaute, 2020), and ecosystem health (Walling & Vaneeckhaute, 2020). Thus, the efficiency of agrochemicals depends on conflicting socio-ecological objectives, leading to a complex multi-objective decision-making process (Pastori et al., 2017). Nonetheless, African farmers can significantly improve their livelihoods while preserving the environment. This objective can be achieved by maximizing the efficiency of applied fertilizers which can contribute to sustainable agricultural intensification, and indirect reduction in carbon sequestration when considering enhanced yield without expanding arable land at the expense of forested areas and woodland.

Dissemination of improved fertilizer use needs to be accompanied by appropriate guidance on sustainable use so that agricultural growth does not occur at the expense of the environment. Cooperation can foster participatory learning and encourage knowledge transfer between farmers and through training sessions provided by extension services.

2.6.5 Approaches to support the adoption of more sustainable management

The findings of this study demonstrate that the policy design, supported by subsidies, influenced the update of drip irrigation, and induced a change in crop choice. Many African countries have established ambitious policy frameworks to promote the economic growth of the agricultural sector. For instance, the exacerbation of existing drought periods influenced policy reform and led to substituting cash crop cultivation (e.g., cotton) with food crops in irrigated perimeters. This agricultural drought-driven policy contributed to ensuring food security in Sudan, but failed to maintain the economic viability of the agricultural sector and led to unsustainable use of water resources (Nakro et al., 2022). The dependency on subsidies can have unintended consequences by disrupting adaptation strategies aiming to reduce food insecurity. In particular, when a subsidy targets the promotion of high-value crops at the expense of others considered non-strategic, it can be a driver of biodiversity loss and limit income diversification and hence resilience to market shocks. Therefore, subsidy design must be undertaken with care, and impacts reviewed at regular intervals. This could involve implementing adaptive management strategies, where subsidies are revised based on the outcomes observed during periodic assessments. These assessments should include both economic and environmental indicators, such as changes in water use efficiency, crop diversity, and farmer income levels. Engaging stakeholders—including farmers, local communities, and policy makers—in the evaluation process is also essential, as it ensures that policies are responsive to the evolving needs of the agricultural sector. Furthermore, pilot projects can be conducted before full-scale implementation to test the potential impacts of subsidies and identify any unintended consequences early on. This iterative approach helps ensure that subsidies promote sustainability, minimize risks to biodiversity, and support long-term agricultural resilience.

Another example is the economic impact of policy interventions in changing irrigation practices through water policy restrictions. In South Africa, farmers reduced the cultivated area to meet water crop requirements. However, the gross margin for certain crops such as planted maize increased due to higher yield income recorded for full irrigation in a reduced area (Jordaan & Bahta, 2020).

In African countries, there is a rich variety of national agricultural policies leading to different behavioural responses towards the uptake of sustainable agricultural practices. Yet, to identify targets for improvement and provide mitigation solutions, it is not sufficient to consider only the biophysical and politico-economic drivers of farmers' decision-making, but it is also necessary to account for the collective rules governing farmers' organization (Mekki et al., 2018).

In our study, we highlighted four key management areas where more sustainable approaches could be adopted. For irrigation, fertilizer management, and tillage our respondents largely agreed that collaboration networks would improve the adoption of sustainable practices (80%, 78%, and 75% respectively) and a majority (60%) felt this to be true for the adoption of agroforestry.

These results accord with (Dayamba et al., 2018) who demonstrated the efficiency of the participatory decision-making approach adopted in both Senegal and Mali to support farmers in identifying options to increase farming resilience adapted to their local socio and climatic conditions. Participatory approaches are important but not sufficient. Farmers may reject sustainable farming methods when they do not align with their objectives or are unsuitable for them. This can be seen by the propensity of the new generation of farmers to modernize their farms and engage in sustainable farming practices whereas the older ones are less inclined to learn new farming techniques but focus on securing their livelihood (Venot et al., 2014).

The introduction of new farming practices via a collaborative approach should consider the previous or existing agricultural cooperatives and the co-existence of different farming systems within the same area. Some African governments launched state-led policies relying on a top-down approach with a limited engagement of farmers (Bamoi & Yilmaz, 2021). In West Africa, it was faced with the reluctance of growers to embrace this structural adjustment and the disinvestment in the agricultural sector.

Drawing on the example of North African countries, the agrarian reform cooperatives established in Morocco, to modernize agriculture post-independence faced severe resistance from farmers. They opted out of collective organizations resisting the coercive approach established by the state-driven vision to adhere to these cooperatives (Le Coz, 1968). There is also a need to address farmers’ apprehensions about the state-farmer subsidiarity and that the concerted collective approach will not hinder farmers’ emancipation (Kuper et al., 2009; Petit et al., 2018).

Combining technology transfer and capacity transfer can help lessen the socioeconomic vulnerability inherent in North African countries. This is consistent with the findings of Senyolo et al. (2018) who emphasized the role of skills provision in influencing the adoption of climate-smart practices. This result largely confirms the results of Wood et al. (2014) as well, as showing evidence that access to information and participation in social institutions influenced farmer behaviour and decision-making.

2.7 Study limitations

A primary limitation of this study is its macro-level approach, which, while valuable for identifying broad trends and patterns, lacks the granularity to capture the nuanced decision-making behaviours of individual farmers. Context-specific factors, such as extreme weather events, distinct soil characteristics, or unique cultural practices, may be underrepresented in the analysis. Consequently, the broad policy recommendations derived from this study, while useful at a national scale, may not be entirely applicable or effective in regions with unique challenges. For example, a national policy promoting drip irrigation might prove ineffective in areas where smallholder farmers lack the financial capacity or infrastructure to invest in the necessary equipment, despite the general trend showing its perceived benefits. Similarly, subsidies designed at a national level may fail to account for regional disparities in access to resources, potentially leading to unequal adoption rates and exacerbating existing inequalities.

Relying on survey data gathered from stakeholders and professionals is a practical method for capturing perceptions and identifying trends, yet this approach is not without its limitations. Surveys may introduce biases, including the potential for respondents to overstate socially desirable behaviours or underreport constraints. Furthermore, surveys often fail to capture the dynamic and iterative nature of decision-making, where choices evolve over time in response to new information or changing circumstances. As a result, the study’s findings may overestimate the willingness or ability of farmers to adopt sustainable practices. For instance, while survey responses indicate widespread support for collaborative networks, the actual implementation of such networks may face significant challenges due to social barriers, such as mistrust between stakeholders or power imbalances within farming communities. Consequently, conclusions about the effectiveness of cooperation in accelerating technology adoption might appear overly optimistic when applied in practice.

Another limitation lies in the generalisation of findings across diverse agro-climatic zones. While Morocco serves as a valuable model for arid and semi-arid African countries, its specific environmental, social, and economic contexts may differ from those of other regions. Policies that prove effective in Morocco might not yield comparable results in countries with differing governmental structures, water management practices, or market access conditions. This limits the scalability of the study’s conclusions and could lead to inefficiencies or unintended consequences if similar interventions are applied elsewhere without adaptation.

The study focuses heavily on environmental, economic, and technical factors as key influencers of farmer decision-making while placing less emphasis on the social dynamics that underpin behaviour. Factors such as cultural norms, generational differences, and community relationships can play a pivotal role in shaping the adoption of sustainable practices. For example, older farmers may resist adopting new techniques like no-tillage, even when supported by economic incentives, if these practices conflict with long-standing traditions or personal experiences. Similarly, collaborative networks might struggle to achieve their intended goals if they fail to address underlying social tensions or hierarchies within farming communities. By underestimating the importance of these social drivers, the study risks proposing technically sound interventions that lack the necessary social feasibility to succeed.

To address these limitations, future research should adopt a more integrated approach that combines macro-level trends with granular, context-specific data. This could involve conducting regional case studies, geospatial modelling, or longitudinal analyses to better understand localised factors and their interactions with broader patterns. Mixed-methods approaches that incorporate both quantitative surveys and qualitative methods, such as in-depth interviews or participatory workshops, would provide a richer understanding of the complexities of farmer decision-making. Expanding the geographical scope of future studies to include comparative analyses across multiple countries with similar agro-climatic conditions but distinct socio-economic contexts would also enhance the generalisability of findings and help identify both universal principles and context-specific adaptations.

2.8 Conclusion

This study explores the factors that influence farmers' decision-making in relation to crop choice, tillage, irrigation and fertilizer, to identify constraints and opportunities related to adopting more sustainable practices. We found that current agricultural management practices are impacted by various drivers that compel farmers to change and adapt. Overall, influencing factors tended to cluster around environmental pressures, crop characteristics and water availability with social drivers evidently playing a lesser role. While influencing factors are recurrently generalizable, adaptation strategies are context-specific. Such information can help target policies and innovative techniques adapted to the socio-economic and biophysical environment within which farmers operate. If farmers’ behaviour was found to be impacted by constraints rather than opportunities, subsidies were found to strongly adjust farmers’ behaviour. Moreover, the importance of cooperation in shaping agricultural management practices was highlighted. Farmers need both economic incentives and technical support to enhance their adaptive capacity toward climate change and more sustainable management.

2.9 CRediT authorship contribution statement

Imane El Fartassi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration. **Alice E Milne:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. **Rafiq El**

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3 Adaptations in agricultural water management in arid regions: modelling farmer behaviour and cooperation on irrigation sustainability

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3.1 Abstract

Climate change has severely disrupted weather patterns and heightened drought and extreme weather risks in arid and semi-arid regions, requiring adaptations to crop and irrigation strategies to sustain food production. This study develops a set of quantitative methodological approaches describing crop and irrigation management strategies, with a focus on groundwater management and drip irrigation adoption, so to identify influential factors driving decision-making. Extensive interviews were conducted with 70 farmers in Al Haouz Basin providing insights into the motivations for crop and irrigation choices. Inductive coding was used to evaluate qualitative responses, and data was further analysed to determine how farm size and tenure influenced decision-making. An integrated modelling approach based on a combination of theory of planned behaviour and structural equation modelling was used to interpret drivers of irrigation management strategy. The results show large-scale farmers transitioning to more profitable and drought-resilient olive cultivation while falling groundwater levels and soil salinization prompt concerns over declining yields. *Attitudes* toward drip irrigation efficiency, maintaining groundwater supply, and preventing increases in groundwater salinity influence farmer's *intentions* regarding their groundwater usage. Land ownership confers greater long-term perceived control over sustainable water use. Complexities related to subsidy applications and land tenure deter drip irrigation adoption, especially among smallholders, constraining climate change resilience. Our study examines key drivers and policy implications

around evolving crop and irrigation practices. It contributes to understanding farmers' coping strategies and presents a foundation from which to develop evidence-based policy reforms enhancing agricultural and water sustainability across arid and semi-arid regions.

3.2 Highlights

- Qualitative interviews were conducted to understand irrigation and crop management behaviour
- Integrating qualitative interviews with structural equation modelling reveals trade-offs between short-term gains and long-term sustainability under policy/climate scenarios.
- *Attitude* and *Perceived Behavioural Control* strongly influence farmers' irrigation management *intentions.*
- Farmers' *intentions* significantly shape irrigation *behaviour.*
- Farmers have limited capacity for proactive mitigation measures.
- Cooperative groundwater management is vital for addressing drought-related challenges.

3.3 Introduction

Climate change is exacerbating water scarcity in arid and semi-arid regions, and so poses a major risk to agriculture and food security. Declining and increasingly variable rainfall coupled with rising evapotranspiration drastically strains surface and groundwater resources available for irrigation of crops (Dessalegn & Merrey, 2015). Excessive pumping driven by expanding irrigation has depleted aquifers. Heightened agricultural water demand amid declining and less reliable supply has sharpened competition over limited resources, creating social tensions and governance challenges (Gleeson & Richter, 2018). Implementing shared irrigation infrastructure systems and coordinated management practices is critical but faces notable obstacles.

Studies from sub-Saharan Africa highlight issues like conflict over dwindling surface and groundwater resources, deficiencies in system maintenance, and inequitable water distribution as supplies tighten (Meinzen-Dick, 2014; Muchara et al., 2014). In the Middle East and Africa, unregulated groundwater abstractions have strained groundwater levels, while farmer associations have struggled to manage deteriorating surface irrigation networks (Garces-Restrepo et al., 2007; Mohammed Rachid Doukkali, 2005). As climate change exacerbates water scarcity, there is an urgent need to address collective action problems through irrigation reforms and investments.

With climate change increasing reliance on groundwater for reliable irrigation (Bordbar et al., 2023), unrestrained pumping driven by individual interests threatens this critical resource's long-term sustainability (Dessalegn & Merrey, 2015). In the absence of collective governance, farmers' irrigation decisions often prioritize personal objectives over shared long-term sustainability (Harik et al., 2023; Lang & Ertsen, 2023). Developing inclusive groundwater management frameworks that account for diverse motivations, constraints, and social dynamics is vital to balance production goals with resource preservation (S. Foster & Garduño, 2013; Rodríguez-Flores et al., 2023).

Excessive water withdrawals during peak crop demand cause falling groundwater levels and alterations to aquifer hydrogeology over time. Continuous evaporation can also create saline groundwater through the precipitation of salt minerals when arid conditions limit the leaching of accumulated salts (Yechieli & Wood, 2002). Such dynamics currently prevail in arid and semi-arid regions, with overexploitation and rising salinity (5 dS/m) threatening the sustainability of irrigation resources (Salman & Pek, 2020). Community-based approaches that build shared understanding and collect farmer perspectives can improve compliance and equitable outcomes.

The rapid expansion of individual drip irrigation systems, while more efficient in terms of water use compared to traditional irrigation methods, can incentivize unsustainable groundwater extraction. This is because the increased efficiency often leads to the expansion of irrigated areas and more frequent irrigation cycles, resulting in greater overall water consumption. Consequently, aquifers are progressively depleted, posing a significant threat to the long-term viability of irrigation (Meinzen-Dick, 2014). Additionally, as individual groundwater use expands (Biancardi & Maddalena, 2018), hidden competition for groundwater resources creates acute water shortages and social tensions among farmers (Dessalegn & Merrey, 2015). However, low awareness among farmers of linkages between individual behaviours and collective impacts hinders the emergence of cooperative solutions.

Agricultural policies have aimed to balance groundwater preservation with promoting water-efficient irrigation adoption, but effectively managing this trade-off poses challenges (Salman et al., 2019). Quota-based restrictions on groundwater extraction can help control depletion but may deter drip irrigation adoption by reducing withdrawals per unit area (Young et al., 2021). Integrative policy approaches that align incentives for precision irrigation with collective governance of pumping may hold promise (Meinzen-Dick, 2014; Rodríguez-Flores et al., 2023). However, evidence on optimal policy design considering farmers' motivations and constraints is lacking (Harik et al., 2023).

With increasing water scarcity and groundwater depletion in arid regions due to climate change, understanding the drivers of crop choice and irrigation choices takes on critical importance. However, research has predominantly centred on an economic rationality perspective for explaining farmers' crop and irrigation choices (Wens et al., 2020). The full range of factors influencing farmers’ decision-making around crop selection remains poorly understood (Kurukulasuriya & Mendelsohn, 2007). Research shows rising temperatures and shifting precipitation patterns associated with a changing climate in semi-arid regions require the adaptation of cropping systems to reduce water demands (Gebrehiwot & Van Der Veen, 2013). Yet few studies examine how these climate pressures interact with farmer preferences, resource limitations, land tenure constraints, market incentives, and social dynamics to shape land management decisions (Arslan et al., 2014; Bryan et al., 2013; Niles et al., 2013). Significant knowledge gaps persist regarding how climate beliefs, local knowledge, and social networks influence the adoption of low water-consuming crops and irrigation (Teklewold et al., 2013). Integrated assessments of the socioeconomic drivers of farmer decision-making are essential to align practices with the needs of vulnerable arid region populations facing climate disruptions.

Here we set out to determine which factors influence crop and irrigation management in increasingly arid environments. To that end, we conducted a set of structured interviews with farmers on crop choices, perceptions of groundwater depletion, drip irrigation adoption, drought adaptation and mitigation strategies, and collective action barriers. We aimed to identify factors shaping on-farm adaptations and reveal leverage points for interventions to support production. We identified emergent themes through inductive coding analysis from the interview responses and translated these to an integrative theoretical modelling approach combining the theory of planned behaviour (TPB) and structural equation modelling (SEM). The TPB allows us to model how *attitudes, subjective norms,* and *Perceived Behavioural Control (PBC)* influence *intentions* to adopt practices (Ajzen, 1991), while SEM enables analysing the relationships among these factors (Anderson & Gerbing, 1988). We tested the hypothesized pathways through which *attitudes, norms,* and *PBC* influence *intentions* and subsequent adoption *behaviour.* The SEM estimates the strength of these relationships while accounting for multiple interacting variables.

Our objectives were to advance conceptual understanding of the motivations, constraints, and social dynamics shaping crop and irrigation management decisions; and to inform policies and practices that can enhance sustainable agriculture in water-limited regions vulnerable to climate disruptions.

By modelling the complex interactions influencing farmers' *behaviour*, we provide evidence-based insights to help agricultural communities adapt to changing climate and water pressures. This systems-level perspective of the climatic, technological, and behavioural aspects of decision-making aims to inform integrated solutions tailored to the climate and socioeconomic realities farmers face.

3.4 Methodological approach

3.4.1 Study area

The study area is the irrigated perimeter R3, covering an estimated area of 3800 km^2. It is located in Al Haouz plain, situated in the Tensift basin in Morocco, approximately 40 km to the east of Marrakech (Figure 3-1). The prevailing climatic conditions are categorized as semi-arid continental. This region experiences considerable fluctuations in both annual and intra-year rainfall, with an average yearly precipitation of 250 mm. The distribution of the irregular rainfall is skewed towards the winter and spring seasons, accounting for approximately 70% of the total. The potential evapotranspiration (ET_0) is relatively elevated, with the potential to reach up to 1500 mm annually. Winter temperatures tend to dip to an average low of 4°C, while summer temperatures soar to an average high of 37°C. The prevalent soil composition ranges from clay to loam in texture. The Haouz Agricultural Development Regional Office (ORMVAH) is the local agricultural office in charge of the management of irrigation water. It manages the irrigation infrastructure and allocates irrigation from dam water according to the scheduling defined at the beginning of the agricultural campaign. The water allocation is based on the dam water level and negotiations with farmers. Farmers using water from irrigation systems are organized in self-ruled associations called Agricultural Water Users Associations (WUA), which are formal organizations that partially enable them to manage and maintain their irrigation system.

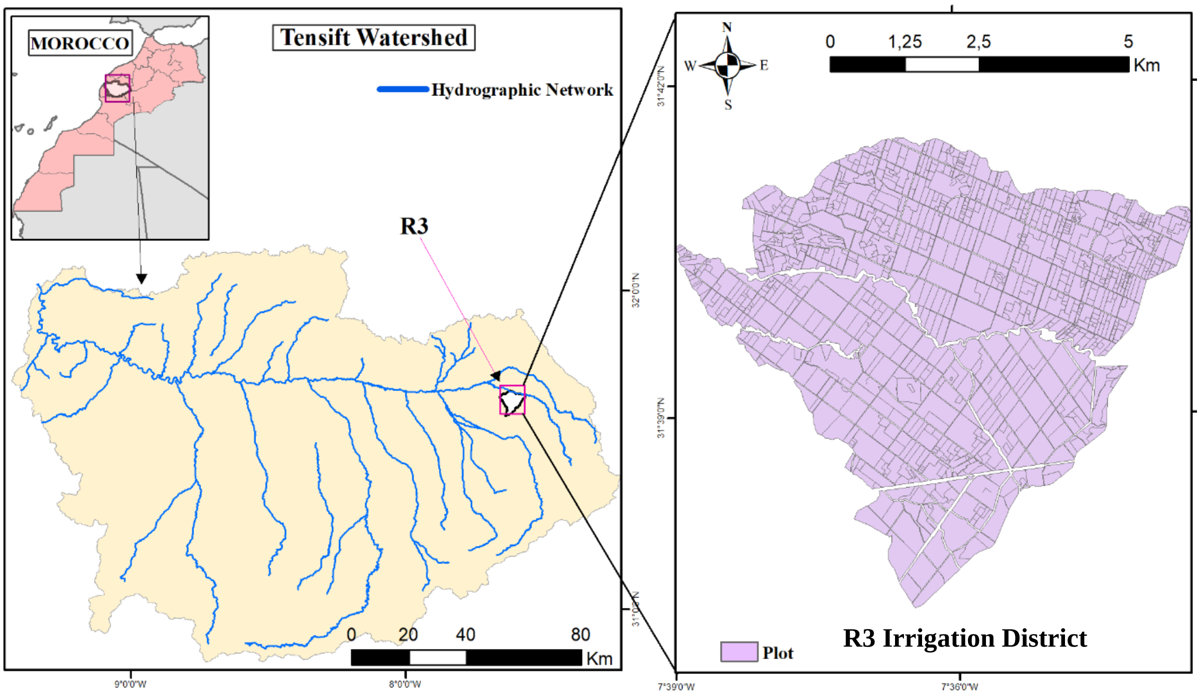

Figure 3-1 Location of the study area: R3 perimeter.

3.4.2 Survey design and data collection

3.4.2.1 Questionnaire prototype development

We held interviews with irrigation experts and regional professionals to gain preliminary insights into water management practices and farming conditions in the study region. Drawing on this and previous work El Fartassi et al. (2023), we developed a prototype questionnaire to elicit information from growers on their crop and irrigation management practices and decision-making. The same irrigation experts and regional professionals reviewed the questionnaire prototype to ensure consistency and adaptability to the agricultural conditions in Morocco. Their review involved evaluating the clarity of the questions, the appropriateness of the terminology used, and the relevance of each question to the local agricultural context. They provided feedback to help align the questions with the specific challenges faced by farmers in the region, such as issues related to water scarcity, irrigation infrastructure, and local crop preferences. This review process was essential for ensuring that the questionnaire was contextually relevant, culturally sensitive, and capable of capturing the nuanced factors influencing farmers’ irrigation and crop management decisions. By incorporating their insights, we aimed to maximize the accuracy and validity of the data collected from local farmers. The questionnaire was then translated into Moroccan Arabic, the local language. Prior to data collection, the questionnaire underwent ethical review and was approved through Cranfield University’s online research ethics approval system. We tested the questionnaire with a pilot group of six farmers to ensure the clarity of questions. We refined the questionnaire accordingly prior to the formal investigation.

3.4.2.2 Survey structure

The questionnaire comprised five sections. Section one captured farm characteristics like cultivated area, irrigation sources, irrigation systems, cropping patterns, and rotations. Section two examined farmers' perceptions of groundwater issues and satisfaction with surface water allocation. Section three assessed farmers' views on drip irrigation adoption, drought adaptation strategies, and coping with water shortages. Section four focused on information sources used for irrigation decisions, barriers to collective action, and successes in collaborative irrigation practices. Finally, section five recorded farm size and tenure type. Full details of the interview questions are given in Table_ C-1.

3.4.2.3 Survey deployment

Given low literacy rates and limited technology access among the farming population in rural areas of Morocco, we conducted in-person interviews to administer the questionnaire. During these interviews, the questionnaire was completed through an oral discussion to accommodate varying literacy levels. In the initial stage, local agricultural office representatives joined the interviews to build trust and gain farmer support, a strategy that can aid survey participation among hesitant communities (Tindana et al., 2007).

We surveyed 70 farmers, with each interview taking between 30 minutes to one hour. The farmers were selected using the Latin Hypercube Sampling (cLHS) approach, which is a stratified random method designed to ensure comprehensive coverage of the entire study area. During the survey, we faced a few practical challenges. In some instances, farmers were unavailable on-site, or farm locations were difficult to access, requiring us to adapt and choose nearby alternatives. Only one farmer refused to participate. During the survey, we faced a few practical challenges. In some instances, farmers were unavailable on-site, or farm locations were difficult to access, requiring us to adapt and choose nearby alternatives. Only one farmer refused to participate. Despite these challenges, we managed to maintain the sample's representativeness, ensuring it was of sufficient size and diversity for structural equation modelling (Iacobucci, 2010; Wolf et al., 2013). Soil samples were collected during farmer interviews as part of a broader study.

3.4.3 Methods of analysis

3.4.3.1 Descriptive analysis

The data were analysed using R (R Core Team, 2022) and GenStat software (VSN International, 2023). We first assessed if crop preferences and cropping patterns varied significantly according to farm size and tenure type using a Pearson χ^2 test. To categorize farm size, we divided the farms into three groups based on area: small farms were less than 5 hectares, medium farms ranged from 5 to 20 hectares, and large farms were greater than 20 hectares. This classification is commonly used in Morocco (Toumi, 2008). For tenure type, we classified farms as either fully owned by the farmer, partially or fully tenanted, or a combination of owned and tenanted land.

For the qualitative data on factors influencing crop management practices, perceived benefits/disbenefits of irrigation systems, and willingness to cooperate, we used an inductive coding approach to identify themes emerging from responses (Thomas, 2006). It involved reading through the raw qualitative data, assigning descriptive codes to segments of text, and then grouping these codes into broader categories and themes that emerge from the data itself. Subsequently, we assessed whether the willingness to cooperate significantly varied with farm size and tenure type by performing a χ^2 permutation test.

3.4.3.2 Theoretical framework and hypotheses testing

The Theory of Planned Behaviour (TPB) is a theoretical framework for understanding the motivations behind behaviours (Conner & Armitage, 1998). TPB posits *intentions* as the proximal predictor of *behaviour* based on three drivers: *attitudes*, *subjective norms*, and *Perceived Behavioural Control (PBC)* (Figure 3-2) (Ajzen, 1991). *Attitudes* reflect favourable or unfavourable assessments about performing the *behaviour* (Ajzen, 1991). *Subjective norms* encompass perceived social pressures relating to important others' expectations and norms (Rivis & Sheeran, 2003) and *PBC* is the perceived capacity to execute the *behaviour* (Ajzen, 2002).

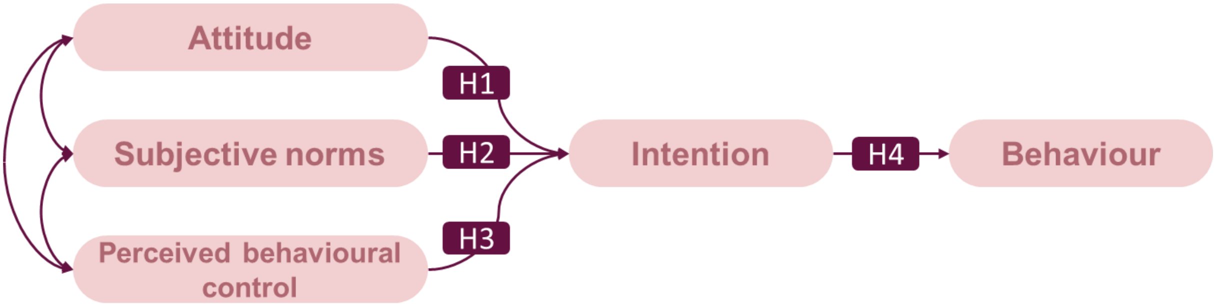

Figure 3-2 Conceptual framework of the Theory of Planned Behaviour.

Based on the TPB, the following hypotheses were formulated regarding factors influencing farmers' groundwater use (G) *intentions* and Drip irrigation (I) adoption.

G.H1-G.H3. Farmers' *subjective norms, attitude,* and *PBC* positively influence their *intention* to use groundwater.

I.H1-I.H3. Farmers' subjective norms*, attitude,* and *PBC* positively influence their *intention* to adopt drip irrigation technology.

I.H4. Farmers' *intention* to adopt drip irrigation positively influences actual adoption *behaviour*. A similar hypothesis was not included for groundwater use because the data collected in this study was primarily focused on the adoption of drip irrigation technologies.

3.4.3.3 Structural Equation Modelling Analysis

Structural equation modelling (SEM) is a statistical technique that estimates relationships between multiple variables simultaneously. It allows the modelling of complex interactions between observed and latent (unobserved) variables (Anderson & Gerbing, 1988). Combined with theory, SEM is a powerful approach to understanding human *intentions* and *behaviours.* For example, it has been applied with the TPB across agricultural contexts to understand farmers' adoption *intentions.* SEM can estimate the relationships between *attitudes, subjective norms, PBC, intentions* and *behaviours.* Related studies have used SEM with TPB to understand water-saving agriculture adoption (Wang et al., 2023), the effect of water availability on crop revenue (Zewdie et al., 2019) and the adoption of low-carbon technology (Yang et al., 2022).

In our study, we applied SEM combined with TPB to model groundwater use and drip irrigation adoption. This enables estimation of how the TPB factors as well as other variables in our conceptual framework relate to and influence farmers' groundwater and technology use. While the *intention* to extract groundwater does not necessarily mean a farmer will adopt drip irrigation, choosing to install drip irrigation systems requires securing access to groundwater. So while the relationship between groundwater usage *intentions* and drip irrigation adoption may be asymmetric, these two factors are closely linked, as reliable groundwater access is essential for supporting drip system installation. Therefore the formulated model serves to explore both *intentions.*

Our SEM analysis of farmers' *intention* to use groundwater and drip irrigation adoption *behaviour* consisted of four primary components:

1) Model specification: We first developed a theoretical model representing the four hypothesized relationships between variables in our framework (described in 2.3.2). This was based on the TPB and previous literature on technology adoption in agriculture. We hypothesized that *attitude, subjective norms,* and *PBC* would positively predict farmers' *intention* to use groundwater and adopt drip irrigation.
2) Measurement Model: We specified a measurement model relating latent variables (*attitudes, subjective norms*, *PBC, intention and behaviour*) to their observed indicators from the survey data (see Table_ C-1). For example, *attitude* towards groundwater use was measured through survey questions on groundwater salinity, groundwater supply and drip irrigation efficiency.
3) Regression Model: We created a regression model with pathways between latent variables according to our research hypotheses. For instance, we modelled a pathway from *PBC* to the *intention* to adopt drip irrigation.
4) Structural Model: We combined the measurement and regression models to create an overall structural model representing the relationships between latent constructs. We also allowed the residual variances between the latent variable of *attitude, subjective norms,* and *PBC* to be correlated to account for commonalities not captured by our survey. We used this structural model to test our theoretical framework.

We fitted the SEM models using the *lavaan* package in R statistical software (Rosseel, 2012). We allowed for freely estimated correlations between observed variables and latent variables.

To interpret the SEM results and assess model fit, we examined fit indices. For overall fit, we looked at the x^2 test, Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), and Standardized Root Mean Square Residual (SRMR). We also assessed the R^2 values for each dependent variable to evaluate the percentage of variance explained by the model. Standardized path coefficients were examined to compare the magnitude of effects between constructs. We checked the convergent validity to ensure the latent variables represented distinct underlying constructs and that the model accurately represented our theoretical framework. Convergent validity was verified by examining the factor loadings of indicators on their respective constructs. We calculated the Kuder-Richardson

Formula KR-20 value to assess the internal consistency reliability of binary variables. The normality assumption was checked using the Shapiro-Wilk Normality Test.

For the SEM analysis, we used diagonally weighted least squares (DWLS) estimation along with non-linear optimization through the Nelder-Mead algorithm.

3.5 Results

3.5.1 Descriptive statistics

The participants were predominantly male (98.8%, n= 69), with only one female. Farmers with access to dam-driven irrigation were members of local Water User Associations (WUAs); 41.4% of the total farmers were WUA members. The participants included farm owners (67.1%, n=47) and renters (32.9%, n=23). Farm sizes fell into three categories: small (<5 ha; 18.6%), medium (5-20 ha; 37.1%), and large (>20 ha; 44.3%). We did not find a significant interaction between farm tenure and farm size.

3.5.2 Crop choice

Of the farmers interviewed, 57 out of 70 were cultivating olive trees. Cereals, horticultural crops, forage, and pulses were grown by 50, 32, 30 and 25 farmers, respectively. The permutation test for the association between crops and farm size showed evidence that crop choice depends on the farm size **(p=0.008)**. Large-scale farmers tended to cultivate more olive trees compared to small- and medium-scale farmers.

Monoculture was adopted by 40% of participants (n = 28), while 17% practised intercropping. Notably, 43% (n = 30) engaged in both cropping approaches. We found no significant association between farm size and cropping pattern.

The survey highlighted a shift away from cereals. The most frequently cited factor was drought susceptibility (6/14 responses), impacting cereal yields. Consequently, cereals are being replaced by olive trees (5/14 responses) which were perceived as more drought (3/14 responses) and salinity (1/14 responses) tolerant. Drip irrigation adoption, which is better suited to perennial crops, has also propelled this transition

(1/14 responses), and poor cereals marketability (1/14 responses) was also mentioned.

While certain farmers have transitioned to olive production or horticulture (2/14 responses), the survey showed that multiple agronomic and economic factors limit the feasibility of horticultural crops for many farmers. Recurrent drought was a major issue (12/32 responses), along with concerns that tree canopies limit yields of intercropped horticulture (5/32 responses). Complex management demand posed additional challenges (3/32 responses), while expensive inputs added financial burden (2/32 responses). Limited market demand also undermined profitability (4/32 responses). Declining soil fertility affected cultivation as well (4/32 responses). Storage difficulties further compounded the challenges (1/32 responses).

The survey disclosed drivers of intercropping abandonment, mainly the inhibitory canopy cover effect (7/11 responses) and persistent drought (4/11 responses).

3.5.3 Drought management

Most farmers (59/70) reported being impacted by water shortages. Key consequences included increased use of electricity/gas for groundwater pumping (36/59). The energy consumption contributes to a costly production (23/59), consequently impacting profitability as noted by (11/59). Furthermore, farmers also spoke of reducing the area they farmed (27/59) and commented that yields were lower (23/59).

In response to these challenges, limited adaptation strategies have been employed. Notably, 26 out of 59 respondents had chosen to deepen existing wells and boreholes, while 8 out of 59 had resorted to digging new wells. When asked about strategies they would have adopted to lessen the effect of water shortages a majority (48 out of 59 responses) lacked contingency plans. Of the farmers not impacted by water shortages, 4 out of 11 had not developed a pre-emptive coping strategy. Conversely, 3 out of 11 respondents had begun adopting drought-tolerant crops.

3.5.4 Cooperation

Farmers expressed a low propensity to cooperate with farmers to mitigate water scarcity (37/70). Another 12 were hesitant but open to cooperation contingently. We found no significant differences between the willingness to cooperate and farm size and tenure.

Key deterrents were perceived lack of benefits (29/37) and reluctance to experiment with new crops (3/37), as the currently cultivated crops are perceived to be the most suited for the local conditions of the region. Another factor was that farmers often have irrigation needs at the same time during drought periods (2/37), which complicates water availability and distribution. Furthermore, apprehension towards constraints imposed by growing similar crops was voiced by one farmer, while another mentioned the need for governmental oversight and farming associations for effective collaboration.

Among those who indicated a tentative willingness to engage in collaborative practices, three respondents highlighted limited water availability as a critical consideration. The perception that the existing crop selection was optimal for the region was reiterated by two farmers, indicating the significance of established agricultural practices. Notably, aspects like government oversight, simultaneous irrigation during droughts, tenure dynamics, and contract terms were mentioned.

In summary, results revealed modest openness to collaborative water conservation, constrained by agronomic beliefs, coordination challenges, and institutional limitations.

3.5.5 Irrigation sources and technology

Groundwater was the predominant irrigation source used (66 participants), followed by dam water (28 participants), surface water (6 participants), and rainfed systems (1 participant). Some farmers reported access to multiple sources. We found no significant differences in irrigation sources based on farm size.

The majority of participants (86%, n=60) reported groundwater-related issues. Lowering of the water table was the most frequently cited problem (83%, n=50). Salinity also emerged as a major challenge (40%, n=24). Additionally, 15% (n=9) expressed concern about wells drying up. In contrast, 14% (n=10) reported no groundwater issues.

The χ^2 permutation test revealed significant differences in perceived salinity presence based on farm size (p=0.04). However, laboratory soil analysis showed no significant differences in salinity among farm sizes. Both large-scale and medium-scale farmers expressed salinity concerns.

Among surveyed farmers, 47 used gravity irrigation and 31 used drip irrigation; some had access to both systems. The permutation test showed evidence of significant differences between the irrigation systems across farms of different sizes (p=0.006). Large-scale farmers were more likely to adopt drip irrigation systems compared to other categories.

The qualitative survey results highlighted the perceived key benefits and challenges associated with adopting drip irrigation. The main advantages were water savings (n=21), automation (n=6), and environmental sustainability (n=4). However, clogged drippers were a major concern (n=6).

While some farmers have adopted drip irrigation, others persist with gravity irrigation. The survey identified factors influencing sustained gravity irrigation use. Major barriers were land tenure restrictions (n=14), insufficient investment capacity (n=10), and low adoption rates among neighbours (n=10), highlighting economic and social influences. Additional obstacles were complex subsidy application procedures (n=8) and limited subsidy awareness (n=8). Other relevant factors were farm size suitability (n=6), crop profiles (n=4), investment constraints (n=4), inadequate private water access (n=3) and lack of technical assistance (n=2).

In our SEM, we analysed the complex interrelationships between various factors influencing groundwater use and drip irrigation adoption. The KR-20 value of 0.72 indicates an acceptable level of internal consistency, suggesting the variables reliably measured the intended construct (Kuder & Richardson, 1937). The χ^2 test for the user model produced a non-significant p-value of 0.819, indicating a good fit. The chi-square test statistic resulted in a non-significant p-value of 0.865. This suggests the model does not significantly differ from the baseline model, indicating a good model fit. The CFI of 1.000 and TLI of 1.056 denote a very good model fit. The RMSEA of <0.001 further indicates excellent fit, and its 90% confidence interval of 0.001 to 0.054 and non-significant p-value confirm the RMSEA falls within acceptable limits. The SRMR of 0.084 can be considered satisfactory for SEM models. Overall, the fit indices unanimously indicate an excellent data-model fit.

The covariance value between the latent constructs of *subjective norms* and attitude was estimated at 0.057, with a standardised estimate of 1.000 (P=0.001), indicating that as *subjective norms* increase, attitude tends to become more favourable. The covariance value between *subjective norms* and *PBC* was 0.044 with a standardised estimate of 0.669 (P=0.002). The positive estimate similarly indicates that higher *subjective norms* are associated with PBC. The covariance between attitude and PBC was 0.101, with a standardised estimate of 0.968 (P=0.002). The positive value reveals that as attitude becomes more favourable, PBC increases.

In the regression analysis, the coefficients for *attitude* and *PBC* predicting *intention* were 0.896 and 0.725, respectively. The positive values indicate that more favourable *attitudes* and greater *PBC* are associated with higher *intentions*. The negative coefficient of -0.745 for *subjective norms* may reflect mediation rather than a direct negative relationship, given the strong positive covariances found between *subjective norms* and other constructs. Finally, *intention* significantly and positively predicted *behaviour* (p<0.001). This suggests that every one-unit increase in *intention* is associated with an expected 0.985 increase in the *behaviour.*

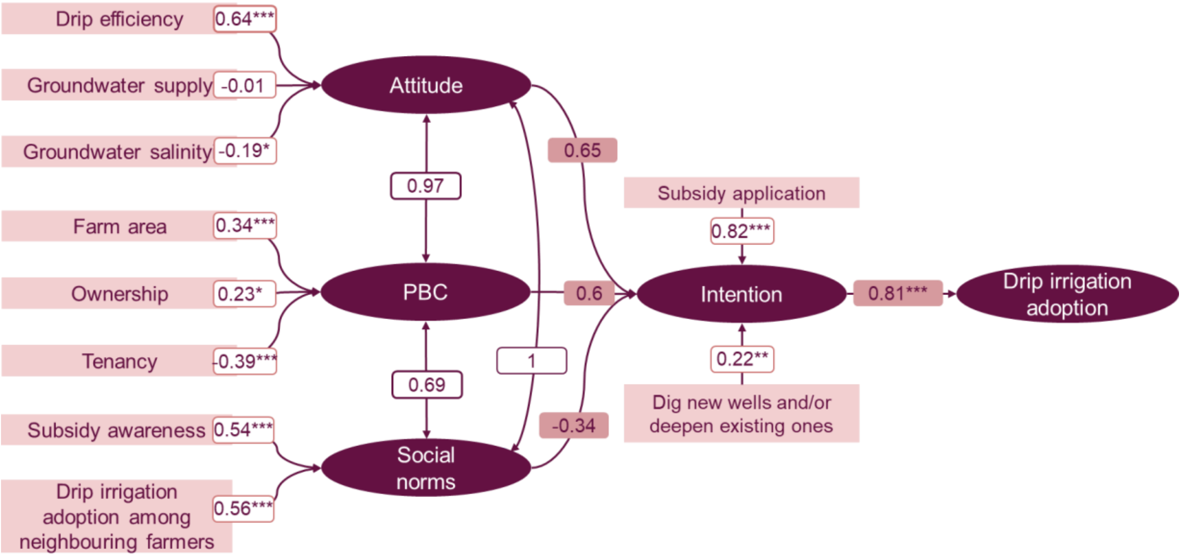

Figure 3-3 Structural equation model fitted to data relating to farmers' intention to deepen existing wells and/or dig new ones, and the adoption of drip irrigation. Round nodes represent latent variables and rectangular nodes are measured variables. Double-headed arrows indicate covariances. Directional arrows linking latent to observed variables show the loadings for each indicator of the latent variable. Causal links between latent variables are indicated by directional arrows. Path coefficients are standardized. *P<0.05, **P<0.01, ***P<0.001

3.6 Discussion

The results of our study provide valuable insights into various aspects of evolving crop choices, irrigation, and drought management.

3.6.1 Shifts in crop choices under drought pressure

We found that large-scale farmers were interested in olive tree cultivation, which is driven by economic and environmental factors. Economically, olive trees offer higher profitability and scalability compared to other crops. The relatively lower maintenance costs and steady demand provide a consistent revenue stream that is well-suited to large farmers' capacity for long-term investment (Papachatzis et al., 2012). While the benefits of olive tree cultivation, such as higher profitability and relatively lower maintenance costs, are appealing (De Gennaro et al., 2012; Stillitano et al., 2016), small-scale farmers often face significant barriers to entry. One major challenge is the initial investment cost required to establish olive orchards, including the purchase of saplings, land preparation, and irrigation infrastructure (Duarte et al., 2008). Additionally, olive trees can take up to three years or more to become productive, which requires farmers to sustain input costs without immediate returns during the initial establishment phase (Tous et al., 2010). This waiting period can be particularly challenging for small-scale farmers with limited financial resources, who often prioritize crops that generate quicker returns to meet their immediate household needs and cash flow requirements (Sgroi et al., 2015). These barriers make olive tree cultivation more viable for large-scale farmers, who generally have greater access to financial resources and can invest in longer-term ventures (Colombo & Perujo-Villanueva, 2019; Stroosnijder et al., 2008). Environmentally, olive trees are perceived as more drought- and salinity-tolerant compared to cereals. These characteristics, along with the adoption of drip irrigation, which is better suited to perennial crops, make olive cultivation an attractive and sustainable option in drought-prone and saline regions (Morgado et al., 2022). However, a crucial emerging threat to olive cultivation, particularly for the Mediterranean region, is the spread of *Xylella fastidiosa*, a plant pathogenic bacterium that has severely impacted olive groves in Europe, especially in Italy and Spain (EFSA, 2015; Saponari et al., 2017). *Xylella fastidiosa* causes symptoms such as leaf scorch, dieback, and eventual tree death, leading to considerable economic losses and reduced olive oil production in affected regions (Schneider et al., 2020). Given the interconnected nature of Mediterranean agriculture, the spread of *Xylella fastidiosa* represents a significant risk to Moroccan olive production as well. Morocco's increasing focus on olive cultivation as a key economic crop makes it highly vulnerable to such transboundary agricultural threats.

The potential spread of *Xylella fastidiosa* to Morocco could have serious implications for farmers, particularly in arid and semi-arid regions where the resilience of agricultural systems is already compromised by water scarcity and soil salinity. Proactive measures, such as monitoring and phytosanitary controls, are essential to prevent the entry and establishment of this pathogen in Moroccan olive orchards. Furthermore, regional cooperation and sharing of best practices for disease management will be critical in mitigating the risk and safeguarding Morocco's olive sector.

Our study also identified the increasing challenges related to the cultivation of horticultural and cereal crops. The high input costs, limited market demand, and declining soil fertility were reported to undermine the profitability of these crops and threaten the farmers' economic stability and income diversification. Furthermore, intercropping horticultural or cereal crops with olive trees can be inhibited by the shading effect of the tree canopy and the complex agroforestry management required, as noted by Temani et al. (2021). The decline in cereals and horticulture may have unintended consequences across economic, agricultural, and environmental domains. The reduced on-farm diversity could negatively impact soil health and biodiversity over time through loss of crop rotations (Morgado et al., 2022).

The transition from cereal and horticultural crops towards intensive olive cultivation reflects the adaptability of farmers in responding to evolving market conditions and environmental constraints. This shift can boost productivity but reduces on-farm diversity, highlighting the need to support sustainable and economically viable practices. Thus, there is a need for further research and policy considerations to support and promote sustainable and economically viable agricultural practices, especially in regions where environmental challenges are a prevalent concern. Integrated solutions like drought-resistant crop varieties (Kaya & Ugurlar, 2023), technical support (Pitt, 2021), market access (Hossain et al., 2022), and sustainable land and water resource management (Gathala et al., 2021) warrant consideration.

3.6.2 Groundwater use

Our participants overwhelmingly (83%) expressed concerns over falling water tables, which they indicated have reduced farming productivity and crop yields over time. Specifically, farmers reported that declining water availability during critical stages of cropping season has led to lower yields. This aligns with research showing groundwater depletion decreasing agricultural outputs in arid regions (Mkilima, 2023; Silatsa & Kebede, 2023). Around 15% of respondents reported wells drying up, directly limiting water availability for crops. Some participants didn’t encounter these issues due to variations in local hydrogeological conditions.

An apparent discrepancy emerged between perceived salinity presence across farm scales, based on farmer self-reports, and measured soil salinity from laboratory analysis. While large-scale and medium-scale farmers reported greater concerns about soil salinity (40%), laboratory analysis of soil samples did not find significant differences in salinity levels between farm sizes. The self-reported salinity perceptions may reflect greater awareness and concern among larger farms rather than objective differences in soil properties. Participants who manage large farms may be more attuned to potential productivity losses from salinity, prompting cautious attention to early-stage soil degradation. Higher salinity damages soil health and crops, further reducing yields and the accumulation of salt can also impair water quality and restrict its usability for irrigation (Mkilima, 2023).

Globally, the depletion of groundwater resources in arid and semi-arid regions demonstrates an urgent need for careful management. In these cases, *subjective norms* and networks of farming stakeholders (farmers, retailers, agronomists, authorities, …) can emerge as key to sustainably managing resources. Their social capital enables collaborative action among institutions preserving groundwater.

Through our SEM analysis, we found that groundwater scarcity does not substantially impact attitudes. Unexpectedly, common concerns over salinity negatively affected attitudes without corresponding usage reductions. This suggests farmers remain attracted to groundwater, due to subsidy incentives for drip irrigation and the increased productivity it enables. Although farmers may express concerns about groundwater depletion and the sustainability of water resources, the immediate economic benefits and increased productivity often outweigh these long-term concerns. Subsidies for drip irrigation, which improve water use efficiency, may also unintentionally encourage farmers to expand irrigated areas or intensify water use, thereby exacerbating groundwater overexploitation. This finding aligns with Boularbah et al. (2019) and Kuper et al. (2018) that in collective irrigation systems where water resources are scarce and unpredictable, there is a tendency towards groundwater overexploitation.

In our study, we investigated whether different land tenure types —specifically ownership and tenancy— influence PBC and, subsequently, resource extraction decisions. Our findings suggest tenure impacts the *intention* to use groundwater and adopt drip irrigation. The contrasts between ownership and tenancy models become evident when considering how farmers make specific actions and investments under each framework. Ownership cultivates greater perceived control and stewardship, leading to more sustainable groundwater and irrigation practices, while tenancy constrains perceived control and focuses extraction decisions on short-term yields. This echoes Sugden (2014) observation that insecure tenure and high rents deter tenant farmers from drilling wells. Given potentially shorter land use, tenants may prioritize extracting from shallower, existing wells over costly new drilling. These investment discrepancies highlight how tenure shapes resource management strategies with significant sustainability implications.

3.6.3 Drip irrigation

The lowering of the water table highlights the pressing need for sustainable water management practices. In this respect, drip irrigation promotion has garnered attention (El Gueddari, 2004). Kuper et al., 2018 highlight the pivotal role of groundwater in enabling expanded drip irrigation, within the sociocultural contexts of state subsidies and farmers' willingness to adopt the technology. Within this socio-economic landscape, Kuper et al. (2018) describe a dual paradox - despite efficiency, drip irrigation exerts added pressure on groundwater.

We found a positive association between *subjective norms* and *attitude*. Whilst we acknowledge that this association is not necessarily causal, societal and peer influences can strongly shape perceptions of this technology. As *subjective norms* shift, *attitude* also changes, potentially impacting willingness to adopt drip irrigation. Similarly, we observed a positive covariance between *subjective norms* and *PBC*. *Subjective norms* can help strengthen confidence in installing drip irrigation. Consequently, changes in *subjective norms* can boost farmers' *PBC*, making them more likely to translate their *intentions* into actual *behaviour.*

Our results reveal large-scale farmers’ significant inclination towards drip irrigation. This traces back to the 1980s in Morocco when companies provided free installation, leading to substantial yield increases and expansion of the technology (Benouniche et al., 2014). Noticing this shift, the government developed a keen interest in drip irrigation, with many large landholders successfully securing subsidies to acquire equipment. In this context, government incentives aimed to encourage adoption for increased productivity, income and water savings, with subsidies found to alleviate financial barriers (Heumesser et al., 2012). However, despite a 100% subsidy for smallholders, perceived obstacles around lengthy procedures still hinder uptake by this group. Furthermore, interviewed farmers emphasized land tenure barriers, with landowners showing higher adoption rates than tenants. This divergence could stem from shorter tenant time horizons on land or complex financing procedures deterring subsidy leveraging. While further investigation is needed, preliminary results indicate land tenure systems could interact with institutional contexts to shape technology adoption. Thus, policies may falter without assessing land issues and clarifying how programs could better accommodate all producers

Our analysis reveals key dynamics influencing groundwater usage *intention* and drip irrigation adoption *behaviours.* Despite the high level of concern about groundwater depletion expressed by 83% of respondents, the economic benefits and increased productivity associated with groundwater use often drive farmers' decisions. The adoption of drip irrigation, supported by subsidies, plays a dual role—it promotes efficient water use but can also incentivize greater reliance on groundwater to maximize productivity. This highlights a discrepancy between the expressed concern for sustainable groundwater use and the economic incentives that influence farmers' behaviours, suggesting that while farmers are aware of the risks, their actions are shaped by immediate economic priorities and the availability of subsidies. Of the three theoretical drivers of *intention*, we find attitude exerts the strongest positive relationship in both contexts — more favourable *attitudes* are associated with heightened *intention* to use groundwater and adopt drip irrigation. *PBC* also positively predicts *intention.* Strategies improving *attitude* and *PBC* can effectively strengthen *intentions* to act. The negative *subjective norms* coefficient in regression may appear counterintuitive. However, it suggests the direct impact of *subjective norms* on *intention* may be weaker relative to *attitude* and *PBC*. Although *subjective norms* may not directly increase *intention*, their influence is offset by the positive relationships they have with *attitude* and *PBC*. Interventions should reinforce positive *attitudes* and *PBC* while considering the more indirect role of *subjective norms.*

The robust positive relationship between *intention* and *behaviour* reaffirms *intention*'s role as a key predictor of actual adoption. Influencing *intention* is critical for driving engagement with drip irrigation. Farm size underscores the contextual relevance of drip irrigation choices within diverse agricultural landscapes. Limited private water access helps explain gravity-flow prevalence (Ameur et al., 2013), while lack of technical assistance further reinforces this choice (Benouniche et al., 2014).

The challenges posed by the limited replenishment of groundwater accentuate the importance of water source availability, which is critical for the sustained operation of drip irrigation. However, the reality of drip irrigation's sustainability impact is complex (Molle & Tanouti, 2017; Sraïri, 2021). Rather than saving water, drip irrigation adoption is associated with unintended consequences like higher crop densities, shifts to water-intensive crops, and reuse of water that was supposedly saved through drip irrigation to expand cultivated areas. These factors collectively increase water consumption versus conserving water. A paradox emerges when governments promote drip irrigation while limiting groundwater use, considering drip irrigation a pump-based irrigation technology.

3.6.4 Cooperation

Farmers have adapted to water shortages by deepening existing wells and drilling new ones, reflecting urgent efforts to secure supply amidst recurring droughts. Our study revealed limited contingency plans for building resilience in drought-prone regions, indicating a lack of proactive preparation and insights into groundwater levels (Laraichi & Hammani, 2018). Our findings of low willingness to cooperate on groundwater-driven irrigation align with previous findings. As Meinzen-Dick (2014) and Mukherji & Shah (2005) note, groundwater lacks the visible and institutional infrastructure that facilitates cooperation, unlike surface water irrigation systems. In surface water systems, infrastructure such as canals, reservoirs, and control gates necessitates coordinated management, requiring users to share responsibility for maintenance, regulate water distribution, and collectively decide allocation schedules. This visible infrastructure fosters regular communication and mutual dependency among farmers, encouraging collective action. In contrast, groundwater is extracted privately through wells, which allows for independent usage and diminishes the need for cooperative agreements, making coordinated management far more challenging. The invisibility of groundwater and lack of transparent monitoring enable individualistic pumping behaviours. Farmers respond to water shortages by increasing their pumping rate, creating a self-reinforcing cycle similar to the “tragedy of the commons”.

However, collective action is possible, as Shah et al. (2007) discuss, pointing to successful community-based initiatives in India and Mexico. For example, in India, groundwater user associations have been established where farmers collectively agree on groundwater extraction limits, share monitoring responsibilities, and regulate well use to prevent overexploitation. Similarly, in Mexico, community-level groundwater management programs involve local groups setting rules for groundwater extraction and collectively investing in water-saving technologies. These initiatives demonstrate that even in the absence of formal infrastructure, effective community organization, trust-building, and locally crafted rules can enable successful collective management of groundwater resources. Our study reinforces that despite less intuitive cooperation for groundwater, social collaboration remains essential for sustainability, requiring comparable trust, communication, and understanding as surface water.

In contrast to studies suggesting that smallholders demonstrate greater openness to cooperation (Meinzen-Dick, 2014; Shah et al., 2007), our findings indicate that farm size does not significantly influence willingness to cooperate, suggesting that this reluctance spans across different farm scales. Other research has also found no significant association between farm size and cooperation (Kerr et al., 2002). This suggests that while farm size may play a contextual role, cooperation cannot be attributed to large versus small-scale agricultural systems.

Incentives and institutional structures are crucial for enabling collective action, as Foster & Garduño (2013) emphasize. Government initiatives can establish ground rules and support local stakeholders in devising equitable governance plans. Our work reinforces that enhancing resilience requires social ingenuity alongside technical solutions. Sustainable groundwater irrigation depends on facilitating communication, building trust, and aligning individual and collective interests.

3.6.5 Challenges of constructing an integrative modelling framework to understand farmers' decision-making

The integrated modelling framework developed in this paper provides a methodological approach for elucidating the multidimensional drivers shaping farmers' decision-making processes. While centred on irrigation technology adoption and water resource usage in a specific regional context, the conceptual scaffolding of qualitative investigation, theory-driven hypothesis modelling, and statistical relationship testing has cross-disciplinary relevance. These components offer a transferable template for constructing integrative explanations of decision-making phenomena in diverse contexts.

Specifically, initial qualitative interviewing allows inductive identification of key *attitudes, subjective norms* and *PBC* beliefs directly from farmer experiences, contextualizing their decisions. Translating these concepts into behavioural theory constructs enables hypothesis formulation regarding relationship dynamics. Integrating this conceptual model with structural equation modelling quantifies influence strengths through statistical testing procedures generalizable beyond the study setting.

Our analytical approach enabled a comprehensive understanding of the complex drivers influencing farmers' decisions, whilst also posing integrative challenges. For instance, while thematic coding exposed perceived obstacles around technology adoption, SEM analysis quantified the relative influence of factors like attitude and PBC. However, effectively harmonising the different data types proved challenging, requiring meticulous integration to ensure compatibility. Moreover, the indirect effects between variables emerged as more intricate than originally hypothesised. Still, the integrated framework provided multidimensional insights into farmers' decision-making processes.

In addition to the integrated modelling approach developed in this study, other methodologies could yield additional insights into farmer decision-making. For instance, choice experiments could be a useful complement to our approach, allowing researchers to quantitatively evaluate farmers' preferences across different scenarios involving irrigation technologies, economic incentives, and policy interventions

(Hanley et al., 1998). Choice experiments can effectively capture trade-offs that farmers are willing to make, providing insights into their decision-making processes beyond attitudinal influences, and could elucidate the importance of specific attributes like cost, labour requirements, and perceived environmental impact (Colen et al., 2016). Discrete choice models (DCMs) are another possible approach, as they allow researchers to model the decision-making process based on observed preferences and revealed behaviour (Train, 2003). These models are particularly useful when combined with stated preference data from choice experiments, providing a richer understanding of behavioural drivers. Additionally, agent-based models (ABMs) have been proposed as a flexible tool for capturing feedback loops, heterogeneity, and emergent behaviours in complex agricultural systems, which are often oversimplified in traditional behavioural models (Berglund, 2015). ABMs can help capture the dynamic interactions between farmers and environmental factors, offering a more nuanced understanding of long-term sustainability outcomes in resource-constrained settings. Furthermore, social network analysis could complement future modelling efforts by investigating the influence of social connections and information flows on farmers' decisions (Borgatti et al., 2009). Such approaches may help elucidate the role of social capital, trust, and knowledge-sharing networks, which were challenging to quantify in the current study.

3.7 Study limitations

The methodological approaches used in this study, while innovative, have certain limitations. One notable limitation is the reliance on structured interviews and the use of inductive coding for analysing qualitative data. While these methods allow for an in-depth understanding of farmers' motivations, behaviours, and constraints, they are inherently subject to biases such as the interviewer's influence on participants and potential misinterpretation of responses. Additionally, the inductive coding was conducted by one person, which could further introduce individual biases. This can affect the reliability of the insights generated and consequently influence the conclusions regarding drivers of crop and irrigation management. The inductive coding approach may also overlook subtleties in responses or cultural nuances, potentially leading to an incomplete representation of the complexities of farmer decision-making processes. Future studies could mitigate these issues by employing a mixed-method approach, incorporating larger-scale surveys alongside qualitative interviews, to cross-validate findings and enhance generalisability.

Another key limitation concerns the use of the TPB and SEM to interpret the drivers of farmer behaviour. While these frameworks are well-suited for examining the relationships between attitudes, norms, PBC, and intentions, they have inherent constraints. The TPB, by design, may oversimplify complex social and environmental influences by categorising them into limited constructs, potentially overlooking contextual factors such as historical land use practices or socio-economic disparities. Moreover, SEM requires the establishment of causal assumptions, which may introduce biases if these assumptions do not accurately reflect the dynamic realities of the farmers' environment. The use of these models may thus limit the interpretation of results, making it challenging to account for the feedback loops and emergent behaviours that are likely present in a real-world, resource-constrained agricultural setting. Future research could explore the integration of more flexible modelling approaches, such as ABMs mentioned above, to capture these dynamics and provide a more nuanced understanding of the interactions between different drivers.

Finally, the study’s geographic focus on the Al Haouz Basin introduces limitations in terms of applicability to other arid and semi-arid regions. The specific socio-economic, cultural, and environmental characteristics of the basin may limit the broader applicability of the findings, as the same drivers of behaviour may manifest differently in other contexts. Future studies should aim to include a more diverse set of regions to validate whether the identified relationships between attitudes, norms, PBC, intentions and behaviour hold across different environmental and socio-political settings. Additionally, exploring the effects of policy interventions in varied contexts could provide valuable insights into how external incentives or regulations can influence irrigation practices and sustainability outcomes.

3.8 Conclusion

Influenced by economic profitability and environmental adaptability, many farmers are transitioning from cereal and horticultural crops towards olive tree cultivation. Groundwater has emerged as the predominant irrigation source, but farmers now face sustainability challenges associated with water depletion and salinity. Our findings show that land tenure type shapes farmers' perceived control and groundwater management decisions, with ownership engendering a more sustainable long-term mindset compared to tenancy. Farmers’ attitudes and *PBC* strongly influence their *intention* to use groundwater and adopt drip irrigation. Notably, *intention* significantly predicts adoption *behaviour*. Influencing *intention* by addressing *attitudes* and *PBC* can promote more sustainable irrigation *behaviours*. Overall, our research emphasizes the need for integrated solutions that consider technological innovations along with social, economic, and policy interventions. Sustainable agricultural and water management in arid regions necessitates strategies that balance productivity, profitability, and environmental resilience while empowering local communities. Further research can build upon these findings to support equitable and sustainable resource use.

3.9 CRediT authorship contribution statement

Imane El Fartassi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Helen Metcalfe:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Alice E. Milne:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data Curation, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. **Rafiq El Alami:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Alhousseine Diarra:** Software, Formal analysis. **Vasthi Alonso-Chavez:** Validation, Investigation, Writing – review & editing. **Toby W. Waine:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Joanna Zawadzka:** Software, Formal analysis. **Ron Corstanje:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

4 An agent-based model of farmer decision making: Application to shared water resources in arid and semi-arid regions

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4.1 Abstract

The study presents an agent-based modelling framework that integrates behavioural and biophysical models to investigate shared irrigation water management in an arid region. The behavioural model simulates farmers' decisions about their water irrigation sources (dam or groundwater) and whether to continue cultivating in the face of drought. This model was parameterised using survey data. The biophysical model component quantifies the impact of water availability and irrigation sources on soil salinity accumulation and its effects on crop productivity. Applied to the Al Haouz Basin, in Morocco, the integrated model shows that increased groundwater access through water abstraction authorization can initially boost productivity but ultimately lead to widespread salinisation and farm abandonment, particularly under climate change scenarios. The results highlight the complex trade-offs between short-term gains and long-term sustainability, emphasising the need for holistic water governance policies that balance individual and collective interests.

4.2 Highlights

- Integrated behavioural and biophysical models simulate shared irrigation management.
- Survey-led parameterization provides new insights for agent-based modelling.

- Initial productivity gains from expanded groundwater access can result in long-term salinization and farm abandonment.
- The modelling approach reveals trade-offs between short-term gains and long-term sustainability under policy/climate scenarios

4.3 Introduction

Climate change projections indicate increasing aridity and water scarcity globally, with concerning implications for rain-fed agriculture (IPCC, 2022). In Africa, these dynamics are already playing out through more extreme droughts and constrained water resources (Masih et al., 2014).The expansion of irrigated agriculture and recurrent drought periods threaten the renewability and sustainability of water resources, with knock-on effects for food security. These dynamics strain dam reservoir resources and force farmers to increasingly rely on unsustainable groundwater withdrawals across the continent (MacDonald et al., 2012; Otoo et al., 2018).

This trend is especially pronounced in arid and semi-arid climates of Africa, where groundwater buffers against acute water scarcity in the short term. However, imbalanced extraction-recharge ratios raise questions about the long-term sustainability of groundwater resources across Africa (Aeschbach-Hertig & Gleeson, 2012). Improving agricultural water use efficiency through integrated management frameworks can help mitigate escalating water stress and economic vulnerability for farmers in drought-prone regions.

In Arid and semi-arid regions, the exacerbation of existing water shortages requires policy interventions towards more sustainable and resilient cropping systems (Mabhaudhi et al., 2016). Theoretically, optimised cropping patterns and irrigation schedules could increase production and water use efficiency at the landscape level. However, individual farmers may have differing objectives and constraints that do not align with these landscape-level goals. Furthermore, cumulative effects from decentralised decision-making can produce unintended regional consequences (Meinzen-Dick, 2014). Integrated management frameworks are needed to balance farm-level interests with broader social and environmental considerations surrounding water resources in drought-prone areas.

Extensive groundwater pumping for irrigation has depleted aquifers and compromised the long-term sustainability of groundwater resources (Gleeson & Richter, 2018). Increasing water withdrawals during periods of peak crop water demand have led to a steady drop in groundwater storage and modifications to aquifers' hydrogeological characteristics. Evaporative losses from irrigation coupled with inadequate natural recharge in many regions (Wada et al., 2010) can induce the formation of saline groundwater through the sedimentation of salt minerals, increasing soil salinity—a condition that often prevails in arid and semi-arid systems during drought (Salman et al., 2019). Given increasing evidence of interconnections between surface and groundwater, integrated management frameworks are needed to account for the wider socio-environmental impacts of intensive groundwater extraction (Foster & Garduño, 2013).

Biophysical models can represent water system dynamics that influence resource availability, quality and crop yields Models quantifying spatiotemporal build-up of soil salinity could provide dynamic feedback to farmer decision-making models (Daliakopoulos et al., 2016). Biophysical models can quantify the dynamics of various environmental processes, which then interact with the decision-making processes of human agents (Letcher et al., 2013).

Agent-based models (ABMs) provide a framework to capture human-environment interactions, allowing the exploration of how changes in environmental conditions shape human behaviour, and conversely, how human decisions impact environmental outcomes over time (An, 2012; Kremmydas et al., 2018).

Prior applications indicate that ABMs can facilitate sustainability assessments for agricultural water usage involving multiple stakeholders (Bulatewicz et al., 2010; Noël & Cai, 2017). However, while some studies have attempted to incorporate human behaviour (An, 2012; Schlüter et al., 2019), the role of human behaviour is often overlooked due to data limitations and difficulty verifying assumptions. Survey data can be used to parameterise behavioural models and capture heterogeneity across decision-makers. An integrated framework coupling biophysical and behavioural models enables holistic and robust climatic and policy simulations for providing insights into coupled human-environment issues (Kremmydas et al., 2018).

Integrating environmental variability factors directly into agent rules creates a coupled mechanism linking salt accumulation from intensive groundwater-dependent irrigation and behavioural adaptations over time. Capturing these environmental feedbacks and constraints is critical for simulating farmers' adaptive behaviours in response to drought, degraded water quality, and other shocks, especially in vulnerable African regions. Integrating behavioural and biophysical models enables a better understanding of the feedback loops between environmental conditions and human decisions (Filatova et al., 2013; Ng et al., 2011).

This paper presents an integrated ABM approach coupling biophysical and behavioural models of agricultural water usage. The approach is applied to a case study of shared irrigation resources across a community of farmers relying on dam releases and/or groundwater in an arid region of Morocco. By capturing the diversity of farmers' water-sourcing strategies and behavioural drivers, the model fosters transparency and enables scenario analyses of policy interventions aimed at balancing sustainable water allocation across heterogeneous users.

4.4 Methodology

4.4.1 Study area

The study region is situated in the Al Haouz Plain of the Tensift watershed in central Morocco (Figure 4-1). The Tensift watershed covers an area of 6000 km2 and includes approximately 3100 km^2 of irrigated area. Across the watershed, groundwater is extracted for several uses including drinking water, leisure activities and intensive agriculture. Groundwater depth has decreased substantially since the early 1970s, with a marked increase in depletion rates since the late 1990s, reaching an average drop of 0.9 m year^{-1} across most of the area.

The main study site is an irrigated area known as “Perimeter R3” (Figure 4-1). It is located 40 km East of Marrakech city and covers approximately 2800 ha. The study area falls within the semi-arid continental climate and is characterized by a large inter- and intra-annual variability in precipitation, with an average annual rainfall of 250 mm.

The soil type is predominantly clay to loam, and the topography varies from 188 to 1453 m above mean sea level. Wheat is the dominant crop in this area (Kharrou et al., 2021)

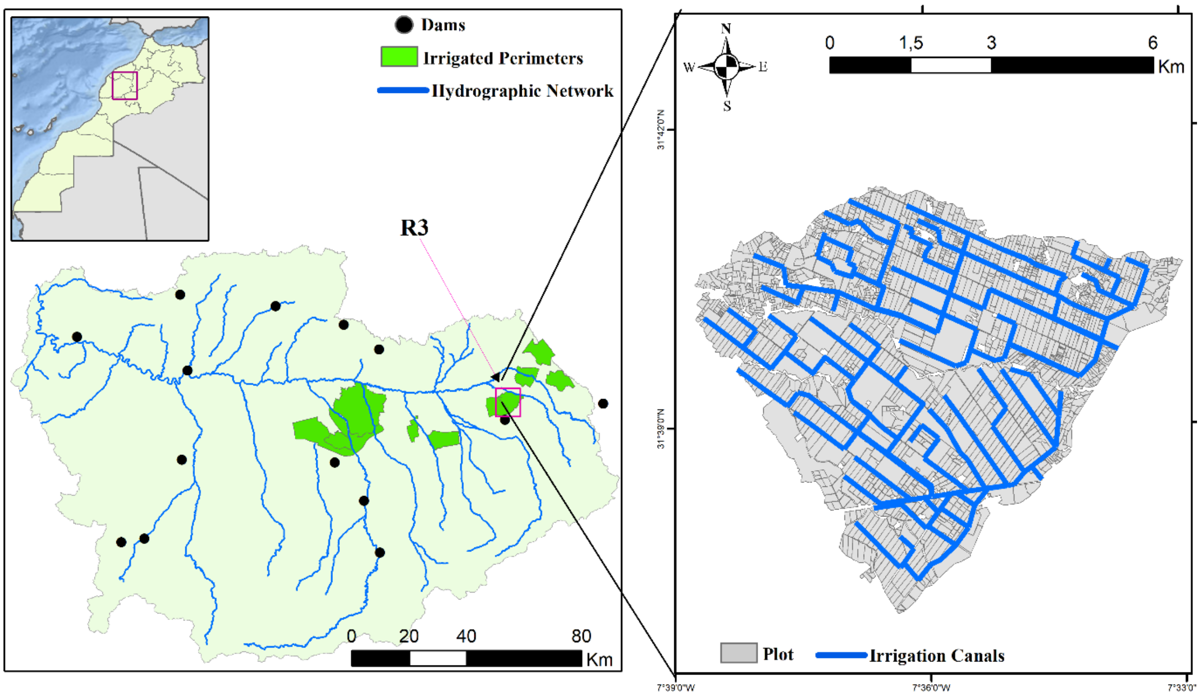


Figure 4-1 Location of the study area: R3 perimeter, Al Haouz Basin, Morocco.

4.4.2 Water allocation and management

To channel water from the dam to the farmed areas, an irrigation infrastructure was installed in the year 2000. There are three different sources of irrigation water in R3: groundwater, dam or river diversions (Duchemin et al., 2009). The Haouz Agricultural Development Regional Office (ORMVAH) is the local agricultural office in charge of the management of irrigation water in the Al Haouz basin. It manages the irrigation infrastructure and allocates irrigation water from the dam according to the scheduling defined at the beginning of the agricultural campaign. The water allocation is based on the dam water level and negotiations with farmers. Farmers pay for the water rights. The water price is determined by the local water authorities and water distribution is based on the land area under cultivation. The water stored in the dam is channelled to the irrigation network. It is then diverted and pumped onto crops, mainly by gravity, through a hierarchic network of overhead concrete canals (Figure 4-2).

Figure 4-2 Irrigation system consisting of elevated concrete canals arranged in a hierarchical structure.

In R3, the irrigation infrastructure can serve an average of 40 ha per tertiary canal. Recently, in drought years, the water allocation is typically 4000 m^3/ha but can be as low as 324 m^3/ha. In extreme drought conditions, the water allocation can potentially reach zero, significantly limiting the available water for irrigation.

All farmers in the irrigated perimeters belong to water users' associations and have a right to dam water. However, not all irrigated areas are covered by the infrastructure, leading farmers without dam access to typically rely on groundwater. The Tensift Watershed Agency (ABH-T) issues permits for groundwater abstraction. In response to ongoing groundwater depletion, the ABH-T has started to limit the number of permits authorised.

4.4.3 Model Structure

The modelling framework combines behavioural and biophysical components to simulate the dynamics of shared irrigation water management in the study region (Figure 4-3). The behavioural model uses an agent-based approach to simulate the irrigation choices and adaptations of individual farmers, who can access water from the dam, groundwater, or a combination of both sources. This agent-based component captures the heterogeneous decision-making processes of farmers and their water-sourcing behaviours over time.

The biophysical model represents the water system, capturing factors such as dam fill rates, soil salinity accumulation, and crop yields. This biophysical component provides the environmental context within which the farmers’ decision-making occurs.

4.4.3.1 Behavioural Model Structure

In the model, agents can be categorized into one of three water-user types: dam-only users, groundwater-only users, and mixed irrigation users.

Dam-only users face the decision of whether to invest in additional infrastructure to access groundwater, in addition to the dam water they currently use. This decision represents a key choice point for these agents.

We based the structure of this decision-making model on interviews conducted with farmers to identify the key influences on their irrigation management choices (El Fartassi et al., 2024). Analysis of the survey data, using structured equation modelling underpinned by the theory of planned behaviour, showed that *attitude* and *perceived* *behavioural control* (PBC) were the most significant factors, while *subjective norms* were not significant, in underlying farmers' irrigation source decisions (for details see El Fartassi et al., 2024). Therefore to model this decision process, we assign each agent variables representing *Attitude* and *PBC*.

The *Attitude* variable reflects the farmer's positive or negative evaluation of using groundwater. This evaluation is influenced by crop yield, which depends on water supply and water salinity. The *PBC* variable captures the farmer's perceived ease of implementing ground-water extraction. This perception is determined by affordability and operational constraints which in our previous analysis (El Fartassi et al., 2024) we showed were related to farm size and ownership.

In our ABM, the *Attitude* variables are each assigned values between zero and one. A value of zero indicates the farmer has a completely negative attitude toward using groundwater, while a value of one means the farmer perceives groundwater as an essential option for irrigation.

Perceived behavioural control is modelled through two components. First *Affordability*, which is represented by a value between 0 (completely unaffordable) and 1 (completely affordable). The second component relates to the *Perceived ability to invest*. This variable is also represented by a value between 0 (completely constrained) and 1 (completely unconstrained) to capture the farmer's perceived ease or difficulty in making long-term investments in the land. In our model, if the agent's *Attitude*, and *PBC (Affordability* and *Perceived ability to invest)* values all exceed a threshold of 0.5, the farmer applies for authorisation to adopt groundwater extraction as part of their irrigation strategy (Figure 4-3). The adoption of groundwater in the model is also influenced by regulatory constraints, particularly the authorisation of new wells. In our model, only a certain number of water abstractions are authorised annually (see 4.4.7 Scenarios). Authorisations are allocated randomly. If the application is successful, the farmer transitions to a mixed irrigation strategy. This approach reflects current practices to some extent, as described in section 4.4.2, where regulatory agencies limit the number of new groundwater wells to manage water resources sustainably. In practice, authorisations are often influenced by factors such as priority given to certain regions or types of farms. In Morocco, authorisations are often influenced by factors such as priority given to certain regions or types of farms. For example, the allocation of groundwater extraction permits is influenced by regional priorities as outlined in the "Plan Maroc Vert" (Green Morocco Plan), which emphasizes the development of high-value agriculture in specific areas, affecting the distribution of water permits (Faysse, 2015). Additionally, in regions like the Souss-Massa basin and the Al Haouz Basin, aquifer contracts have been established as part of efforts to regulate groundwater use more effectively (Mansir et al., 2018). In the Al Haouz Basin, these contracts involve agreements between farmers, local authorities, and stakeholders to collaboratively manage groundwater extraction. By prioritizing allocation based on regional water availability and specific agricultural needs, these contracts help ensure that limited water resources are distributed efficiently. This approach takes into account the local challenges, such as prolonged droughts and varying irrigation demands, to promote sustainable water management practices tailored to the needs of the region.

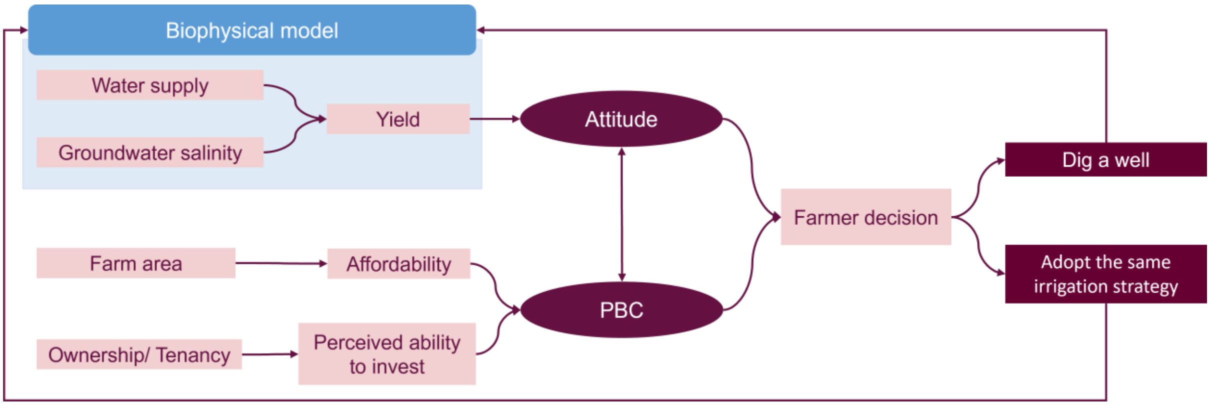


Figure 4-3 A decision-flow diagram illustrating the integration of the biophysical and behavioural models and the key factors influencing farmers' irrigation management decisions.

In our study area, continued drought conditions have led to some farmers abandoning cultivation. The second modelled decision captures this behaviour. It applies to all agents, regardless of their current water source, except those who have only just transitioned to mixed irrigation. We model this by sampling the number of consecutive years a farmer can tolerate a loss in profit from drought from a Poisson distribution with mean λ. If this value is exceeded, then the farmer abandons cultivation.

4.4.3.2 Model dynamics

The model has an annual time step. At each time step, the *Attitude* and *Affordability* variables are updated, and new decisions are made.

We assume that farmers' attitudes towards groundwater usage are influenced by their yield outcomes. To capture this, our model simulates interactions among farmers based on their yield comparisons. Specifically, we update each farmer's *attitude* towards groundwater usage based on the comparative performance of their yields with those using mixed irrigation ($\bar{Y}_{\text{mix}}$) Then the attitude of the dam water user is updated by :

$$A_i(t+1) = A_i(t) + \alpha\,(\bar{Y}_{\text{mix}} - Y_i\,)\ \text{for}\ i = 1, \ldots., n_{\text{Dam}} \tag{4-1}$$

where α is a scaling factor that determines the magnitude of the agent’s attitude and n_{Dam} is the total number of dam users. The attitude adjustment is bounded between 0 and 1 to ensure it remains within a plausible range. In practice, farmers often compare their yield outcomes through informal social interactions, such as discussions at local markets, farmer gatherings, or community meetings. These interactions provide an opportunity for farmers to share experiences, assess each other's practices, and evaluate outcomes such as yield and profitability. In many rural communities, yield comparisons are facilitated through word of mouth, which can influence perceptions and decision-making related to groundwater use and irrigation strategies. This peer-to-peer knowledge exchange is particularly prevalent in Moroccan agricultural communities, where social networks play an essential role in spreading information and fostering the adoption of new practices (Amrouk, 2021). Such comparisons are crucial for our model, as they help simulate how farmers' attitudes towards groundwater usage evolve in response to observed outcomes.

In our model, we assume that a farmer’s *PBC* will be affected by their interactions with others in their social network. To capture this, we use opinion dynamics (Milne et al., 2020)**.** Opinion dynamics refers to the mathematical modelling of how individuals' beliefs or behaviours change over time as they interact with others in their social network (Castellano et al., 2007). In this context, opinion dynamics is used to simulate how farmers' perceptions about agricultural practices, such as adopting new irrigation technologies, evolve based on their social environment. The approach models how individuals' attitudes are influenced through repeated interactions, leading to either convergence of opinions or the maintenance of diversity within the group, depending on the strength and nature of social ties (Acemoglu & Ozdaglar, 2011). At each time step, agents interact with other eligible agents. We assume that the eligibility of agents is a function of farm size and that farmers' opinions about relative affordability are influenced only by the opinions of farmers with farms of similar size (see explanation below).

To update the *Affordability* (x) of the agent i, the model randomly selects up to $n_{\max}$ agents for interaction. The model employs a weighted average approach according to the following equation:

$$x_i(t+1) = w_{i1}x_1(t) + w_{i2}x_2(t) + w_{i3}x_3(t) + \cdots + w_{in}x_n(t) \text{ for } i = 1, \ldots., n_{\max} \quad (4\text{-}2)$$

where w_{ij} is the weight agent i gives to agent j's opinion. The weights must be greater than or equal to zero and sum to one.

In our model, we assume that the perceived ability to invest in the land is affected by the type of tenure which does not change over time.

4.4.4 Initial conditions

In our model, we generate a population of agents that are representative of the farmers in the case study area. The initial conditions are defined in terms of farm area, soil salinity, access to dam water, access to groundwater and type of tenure.

4.4.4.1 Simulated areas

To generate the farm areas for our agents, we first fitted a lognormal distribution to the farm areas reported by the farmers in our survey (El Fartassi et al., 2024). The fitted distribution had parameters μ = 1.88 and σ = 1.20 (Figure_ D-1, Figure_ D-2, Table_ D-1). We then randomly sampled from this distribution until the total sum of the agent's farm areas matched the study region. This resulted in 248 farmers. These farmers were classified into small (<5 ha), medium (5–20 ha) and large (>20 ha) (Table 4-1) (El Fartassi et al., 2024).

Table 4-1 Distribution of farm area according to observed and simulated data.

Farmer typology	Observed total area (%)	Simulated total area (%)	Simulated farmers
Small	31	34	102
Medium	52	49	108
Large	17	18	38
Total	100	100	248

4.4.4.2 Access to dam water

To estimate the surface area having access to the dam water, we assume that the irrigation canals cover a radius of 30m (plots located up to 30m from the irrigation canal can be irrigated). Based on this assumption, 78% of the study area has access to the dam water (Figure 4-1). Therefore, we randomly allocated agents as having access to the dam up to a total area of 78%.

4.4.4.3 Access to Groundwater

For our initial state, we assume that 72.58 % of the simulated population of farmers have access to the dam only, 22.18% to groundwater only and 5.24% to mixed irrigation.

To initialize values for the *Attitude*, and *PBC* variables (*Affordability* and *Perceived ability to invest*), we sampled from beta distributions parameterised to capture the attitudinal differences across irrigation categories, with on average most positive attitudes associated with those who already use groundwater-only and least positive for those using dam only (Table 4-2). We note that setting the initial *Attitude and PBC* conditions of the agents using dam water to low values prevented abrupt shifts to mixed irrigation in the early simulation and let the system dynamics play out.

For initial *Affordability* values, we assigned beta distributions to different farmer typologies (small, medium, and large) based on the concept of economies of scale (Michael, 2009). This approach assumes that larger-scale farmers have higher affordability (Table 4-2).

In Table 4-2, the parameters α and β represent the shape parameters of the beta distributions used to initialise the values for *Attitude, Affordability,* and *Tenancy* across different irrigation categories, farmer typologies, and types of tenancies. The α parameter influences the shape of the distribution towards the higher end of the range, while the β parameter influences the shape towards the lower end. Together, these parameters help determine the skewness of the distribution, enabling us to capture the attitudinal differences observed among various irrigation categories and farmer types.

For instance, a higher value of α relative to β generally results in a positively skewed distribution, indicating more positive attitudes or affordability perceptions within that category. Conversely, when β exceeds α, it results in a negative skew, implying a more conservative or negative outlook.

To simulate initial *Tenancy* values, we characterized 90% of agents as owners and 10% as renters, based on our survey. Separate beta distributions were configured for each type of tenancy, reflecting differences due to ownership status (Table 4-2).

Table 4-2 The proportion of sampled *attitude*, *affordability* and *tenancy* values.

	Sample Size	α	β	Proportion > 0.5
Irrigation category				
Groundwater-only	55	8	7	0.62
Mixed	13	5.5	4.3	0.54
Dam-only	180	6.4	8.6	0.23
Farmer typology				
Small	102	8.4	7	0.71
Medium	108	9	6	0.84
Large	38	10	5	0.95
Types of tenancies				
Owner	223	9.1	5.9	0.95
Renter	25	7.5	7.5	0.64

4.4.5 Biophysical model

Our model describes the dynamics associated with irrigation water supply and yield response.

4.4.5.1 Irrigation resources

We consider two primary irrigation water sources available to the agents in our model: groundwater and dam water.

We assume that the total volume of water available to agents from the dam in the year t is $D(t)$ m^3, and this is given by:

$$D(t) = D(t-1) - W_f(t-1) + r(t-1) \tag{4-3}$$

where $W_f(t-1)$ is the total amount of water allocated to agents from the dam in the year $t-1$ and $r(t-1)$ is the dam replenishment. The main sources of replenishment are rainfall and streams. To estimate the dam replenishment under steady-state conditions, we assume that the water allocated to the agents using the dam under initial conditions is equal to the amount replenished in a non-drought year. This replenishment rate is varied for different scenarios in the model, allowing us to explore the impacts of fluctuating rainfall, streamflow, and drought conditions on dam levels and water availability for users.

Depending on the agents' choices and the extent of the shared irrigation infrastructure, they can choose to irrigate from one source or a mixture with a predefined dam extraction rate $E_D(t)$.

For agents choosing both sources of irrigation, we assume that an agent uses their full water allocation and complements with groundwater extraction. We assume a cap on their needs for dam water equal to the crop water requirement CWR. The dam extraction rate is given by:

$$E_D(t) = \min(CWR, d) \tag{4-4}$$

Where $d = \frac{D(t)}{n_{\text{Dam}}}$.

4.4.5.2 Soil salinity

To capture the observed impacts of using groundwater as an irrigation source on soil salinity (measured as electrical conductivity (EC)), we describe the salinity dynamics for each agent's land (i) using a discretised exponential model following (Ayers et al., 1985):

$$S_i(t) = \max(S_0, \varphi - [\varphi - S_i(t-1)]W(EC_w)) \tag{4-5}$$

where $S_i(t)$ is the salinity of the soil at the time t, S_0 is the lowest plausible soil salinity for that area (See supplementary data for full derivation 8D.5.1), φ is the carrying capacity, i.e., the maximum value that S_i can take, and W is a function of the salinity of the water applied (EC_w).

Based on (Kamal et al., 2021), the water salinity of the Al Haouz aquifer varies from 0.33 to 6.8 dS/cm. To set up our simulation, we assume that groundwater and the dam salinity are equal to 6.8 dS/cm and 0.02 dS/cm. The EC_w in dS/m value is calculated:

$$EC_w = \beta EC_G + (1-\beta)EC_D \qquad (4\text{-}6)$$

where β is the proportion of water used that comes from the ground.

Whilst it is known that using saline water to irrigate can lead to a build-up of salinity in soil (Gurmessa et al., 2022), the complexity of the processes involved and the variation in those processes from location to location hinder the soil salinity quantification from year to year. Ayers et al., (1985) provide equations to relate the salinity of water applied to increases in soil salinity over time based on assumptions about rooting depth and leaching fraction. In our model, we assume that irrigation is done by gravity flow, which has an efficiency of 60% (Bouaziz & Belabbes, 2002). Ayers et al. (1985) estimate that after 3 – 5 years of irrigation with a leaching fraction of 0.4 the soil will have a salinity equal to 0.9 times that of the water applied. Therefore, we assume:

$$W(EC_w) = \left(\frac{\varphi - 0.9EC_w}{\varphi - S_0}\right)^{\frac{1}{3}} \qquad (4\text{-}7)$$

where $S_0 = 0.01$, and φ = 22.

To assign salinity values to each agent’s land, we used the soil salinity values observed from our survey (El Fartassi et al., 2024) and fit an exponential probability distribution. The fitted distribution had mean mu = 4.24 (Figure_ D-4, Figure_ D-3, Table_ D-3). We sampled a single random value for each agent’s land from this distribution. We note that, although large farmers in our survey stressed issues related to salinity, we found no notable interaction between farm size and salinity in our data (El Fartassi et al, 2024). Thus, we allocated random values for each farm.

4.4.5.3 Yield response function

For simplicity, we assume a generic crop based on wheat, which is the most commonly grown crop in the study region (El Fartassi et al., 2024). The yield response function for this crop calculates the yield obtained by an agent given the salinity of the soil in their field (S_i) and the amount of water supplied (w). We assume a multiplicative function of yield response to water and salinity with yield ($Y_i(t)$) given by:

$$Y_i(t) = \Psi(w)Y_r(S_i) \tag{4-8}$$

where $Y_r(S_i)$ is the relative yield salinity response function and $\Psi(w)$ is the water response function.

To describe the response to salinity we adopt the function given by Van Genuchten & Hoffman (1984):

$$Y_r(S_i) = \frac{1}{1 + \left(\frac{S_i}{EC_{e\,50}}\right)^{P_{Y_r}}} \tag{4-9}$$

where EC_{e50} is the value of salinity at which crop yield is reduced by 50% and P_{Yr} is the steepness of the decreasing sigmoidal curve (Figure 4-4a).

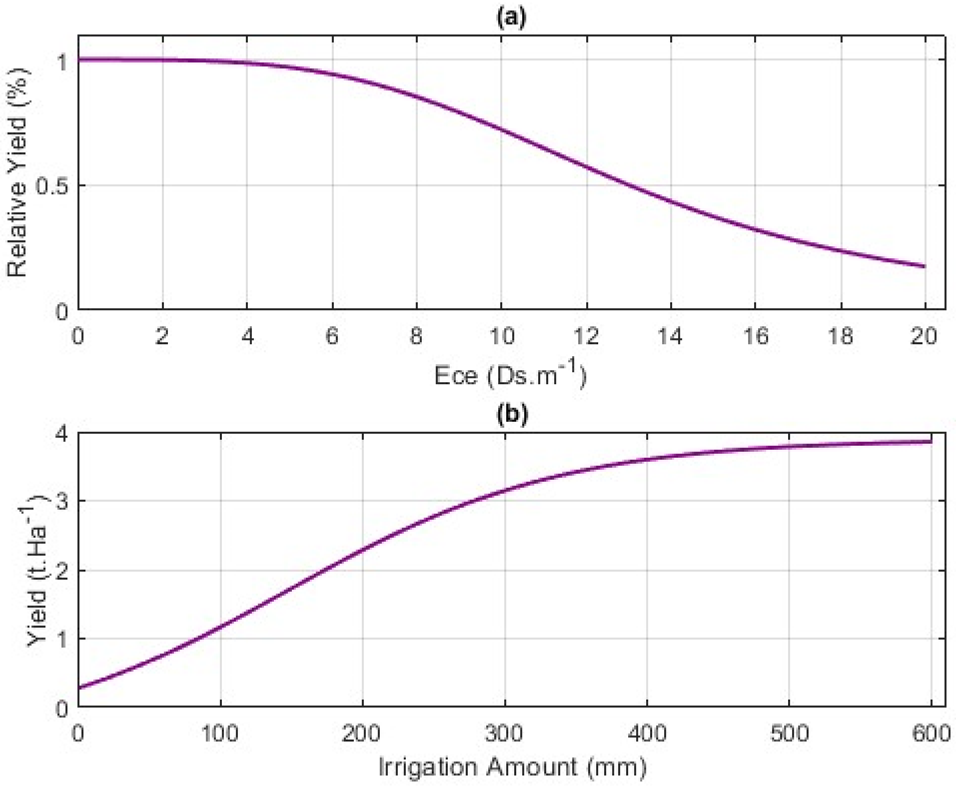


Figure 4-4 (a) Relative yield response function of wheat to the soil salinity levels, represented by the electrical conductivity, where $\boldsymbol{EC_{e50} = 13}$ **dS/cm**, $\boldsymbol{P_{Yr} = 3.6}$. **(b)** Wheat yield response function to varying irrigation amounts.

To parameterise the irrigation yield response model, we used the MATLAB version of the AquaCrop model (AquaCrop-OS) developed by Foster et al. (2017). AquaCrop model parameters for wheat, relevant to our study region were taken from (Oulaid et al., 2024). The typical sowing dates for R3 are from early December through to the end of January. We selected a representative sowing date of 24th December and ran the AquaCrop model with weather data from 2002 – 2003 to derive irrigation dose-response curves for flood irrigation. We fitted irrigation response curves to the AquaCrop-simulated yield data using the GenStat Generalized Linear Models assuming a log-logistic response curve and extracted the Irrigation parameters for a sowing date corresponding to the 24th of December with total irrigation as a dependent variable. (Figure 4-4b, Table_ D-2).

4.4.6 Adoption of Yield-Irrigation Modelling in Evaluating Irrigation Management Strategies in Arid Regions

In this study, a yield-irrigation model was chosen to better align with the objectives of evaluating the effectiveness of irrigation management strategies under varying resource conditions. The primary focus was on understanding how different irrigation inputs affect crop yield in arid and semi-arid environments where efficient water use is a critical concern.

A yield-irrigation model directly relates irrigation practices to yield outcomes. This is particularly advantageous when the goal is to simulate different irrigation scenarios, assess the impact of irrigation technologies (such as drip or mixed irrigation), and understand the relationship between irrigation amount and crop productivity (Boularbah et al., 2019).

In contrast, a yield-potential soil water deficit model is more suitable when evaluating the resilience of crops to water stress without explicitly modelling irrigation inputs. This approach is useful in dryland or rainfed agricultural systems where water inputs are uncontrolled and largely dependent on natural conditions (FAO, 2012). However, in the context of this study, the explicit focus was on irrigation practices and understanding their effect on yield. Therefore, the yield-irrigation model was deemed more appropriate for addressing the key research questions regarding irrigation management in the Al Haouz Basin, where both groundwater and dam irrigation are prevalent.

Additionally, the yield-irrigation model offers a more practical framework for modelling real-time decision-making scenarios, where farmers can adjust irrigation based on current water availability, unlike potential soil water deficit models that largely simulate the response of plants to water scarcity under less flexible conditions (Kuper et al., 2018). Given the study's emphasis on practical water management solutions for improving agricultural sustainability, this approach provided a more effective basis for analysis and interpretation of farmer behaviour and irrigation outcomes.

4.4.7 Scenarios

4.4.7.1 Theoretical scenarios

We considered two theoretical scenarios. In the first, we assume a constant dam fill rate, where the dam replenishment is sufficient to support irrigation throughout. This represents stable water availability. In the second, we consider a decreasing dam fill, where the dam replenishment gradually diminishes over time, simulating reduced water availability (Table 4-3).

4.4.7.2 Realistic scenario

To simulate more realistic scenarios of dam water provision, we used data on water allocation from ORMVAH, spanning from the 1987–1988 season to the 2019–2020 season. This dataset provides information on the actual volume of water delivered for agricultural use (Table_ D-4). In the dataset, water needs are represented as a constant 310 units, based on crop requirements, practices, and environmental conditions. The annual irrigation rate is the ratio of allocated water to estimated water needs, capped at 1 to normalize excess. We fitted a non-parametric distribution (kernel density) to these data to model the variability in the dam irrigation rate. From this fitted distribution, we drew a single set of 50 values, each representing the annual irrigation rate for one of the 50 years of the simulation.

4.4.7.3 Climate change scenario

Expanding on the realistic scenario approach, we introduced a climate change scenario that incorporated a reduction in water availability. In this scenario, we assumed that the dam fill rate would decrease by 12% across the last 10 years of the simulation compared to the values observed in the corresponding years of the realistic scenario (NIC, 2009). This reduction was applied uniformly to each of the last 10 years, reflecting a gradual decline in water availability as projected climate change impacts become more pronounced. This reduction was based on the projected climate change impacts for North Africa, which indicated a clear increase in temperature, a drying trend particularly along the Mediterranean coast, and potential variations in precipitation patterns (NIC, 2009).

Table 4-3 Summary of the different scenarios explored in the study.

Scenario	Description
Theoretical - steady dam fill rate	- Assumes a steady dam fill rate with sufficient replenishment to support irrigation throughout the simulation period.
Theoretical - decreasing dam fill rate	- Considers a decreasing dam fill rate over time, simulating reduced water availability.
Realistic	- Uses historical data on actual water allocation. - Calculates annual irrigation satisfaction rates as the ratio of allocated water to estimated water needs. - Employs kernel density estimation to generate a distribution of satisfaction rates for sampling.
Climate Change	- Builds upon the realistic scenario. - Incorporates a 12% reduction in dam fill rate compared to the last 10 years of the Realistic scenario. - Reflects projected climate change impacts of increased aridity and reduced water availability in the region.

4.4.8 Simulated Policies

We investigated the impact of changing the policy on the number of annual water abstraction authorizations across each of the dam fill rate scenarios described in Table 4-3. We explored the impact of varying the percentage of wells authorized annually with six policy scenarios in which 0, 2.5, 5, 10, 25, and 50% of water abstraction applications are successful.

4.4.9 Simulations

We ran our model for each combination of dam fill rate and policy scenarios. Each simulation lasted 50 timesteps (years). All simulations were initialized with the same starting conditions for agent attributes. For each scenario combination, we ran 20 realisations of the simulations to account for stochasticity in the model. The choice of

20 realisations was based on standard practice in agent-based modelling, where multiple runs are conducted to capture the variability inherent in stochastic processes (Railsback & Grimm, 2011). Previous studies have demonstrated that 20 runs are generally sufficient to ensure that the output variability stabilizes, providing reliable estimates of the model's behaviour without excessive computational costs (Crooks & Heppenstall, 2012).

4.4.10 Sustainability metrics

To quantitatively assess the impacts and trade-offs between different water management scenarios, we calculated sustainability metrics related to agricultural productivity (Yield), environmental health (Salinity), and social impact (Land Abandonment), therefore adopting a holistic approach to sustainability assessment in line with the framework proposed by (Purvis et al., 2019).

4.4.10.1 Agricultural productivity

We recorded average crop yields across all agents using a given irrigation water source at each timestep of the simulation. We compared how productivity levels differed between agents relying on different water sources and how those productivity gaps evolved under varying resource constraints and policy settings. To quantify the impact of our various scenarios we calculated the total yield produced over the simulated period.

4.4.10.2 Environmental Health

We monitored average soil salinity levels, again disaggregated by irrigation water source, over time. To quantity the impact of each scenario on soil salinity, we calculated the count of agents with soil salinity exceeding $EC_{e50} = 13$ dS/m, the value at which wheat crop yield is reduced by 50% (Figure 4-4a).

4.4.10.3 Social Impact

The social impact of agricultural practices is evaluated by examining the total number of agents that have chosen to abandon cultivating and the resulting non-cultivated land area.

4.5 Results

4.5.1 Theoretical scenarios

4.5.1.1 Steady dam fill rate

In the first scenario, we consider a theoretical steady dam-fill rate with a policy where, each year, 15% of all water abstraction applications are successful. Figure 4-5A illustrates the dynamics under this scenario, capturing various aspects of the irrigation system and farmer behaviour. Initially, the yield is similar across all irrigation users. Over time, the yield for groundwater users declines due to increasing soil salinity, which adversely affects crop productivity. In contrast, the yields for dam users and mixed irrigation users remain relatively stable, given that they are less or not impacted by soil salinity issues (Figure 4-5A (b)).

The number of groundwater users decreases sharply after around 15 years, corresponding with the rise in soil salinity (Figure 4-5A (c)). The number of mixed irrigation users increases initially, as some dam users switch to mixed irrigation to supplement their water supply (Figure 4-5A (d)).

Overall, the results indicate that while the dam fill rate remains constant, dam and mixed irrigation users can maintain stable yields and low salinity levels for some time, whereas groundwater users face faster significant challenges that result in a decline in agricultural productivity and increased land abandonment.

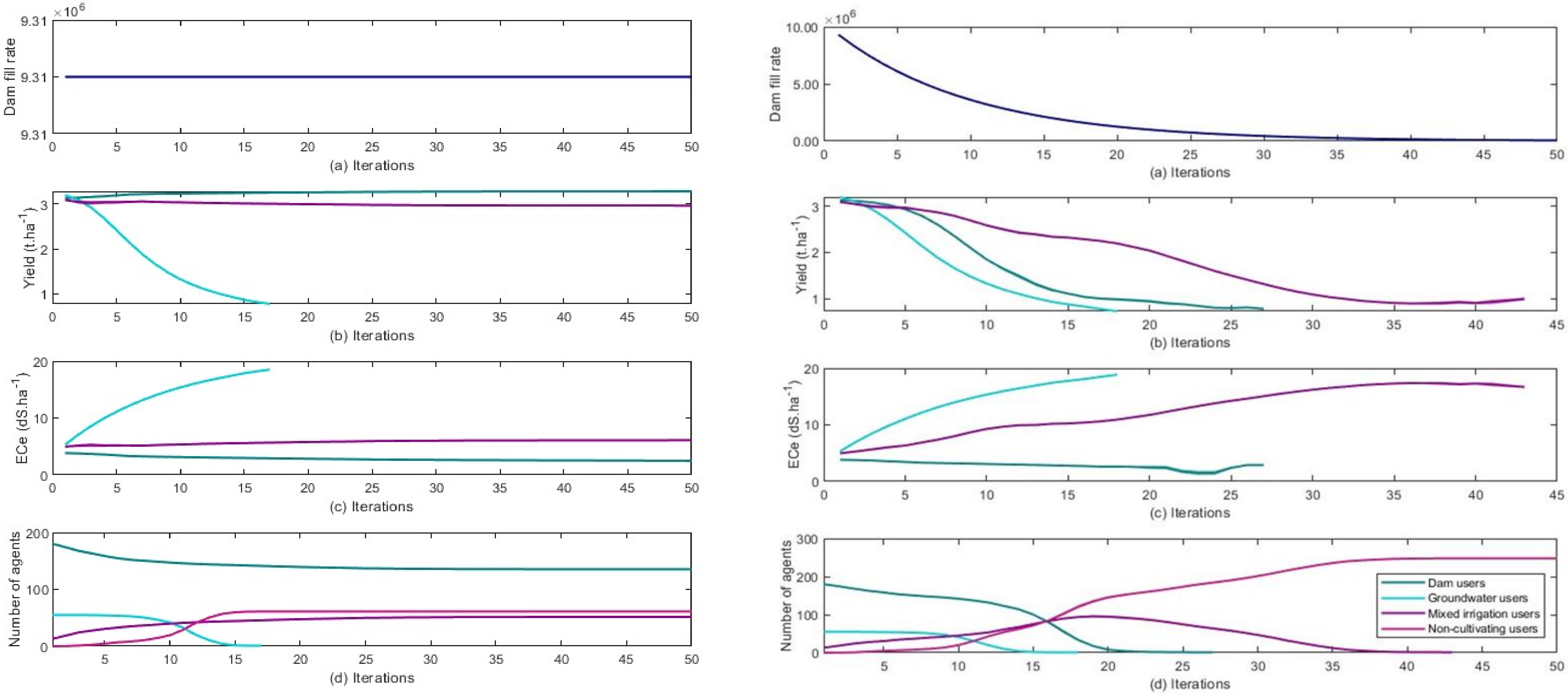
4.5.1.2 Decreasing dam fill rate

As with the previous scenario, we consider a decreasing dam fill rate scenario where, each year, 15% of all water abstraction applications are successful (Figure 4-5 B).

Initially, the average simulated yields were similar across all groups (Figure 4-5B (b)). Both the groundwater users and the dam water users experienced sharp declines in yields, with both groups reaching zero yields after about 18 years and 25 years, respectively. Mixed irrigation users also saw a decline in yields, but at a slower rate than the groundwater users, indicating they were less affected by salinity but still impacted by the overall water scarcity. For the dam-only users, the decline in yield was directly related to the increasingly limited water availability. For the groundwater and mixed irrigation users, the average yield reductions were linked to the buildup of soil salinity from groundwater use. Initially, the dam-only users had marginally higher average yields than the mixed irrigation and groundwater users. The limited water resource became the dominant factor, and the mixed irrigation users had the highest average yields over time.

At the start of the simulation, all irrigation user types exhibit relatively low EC_e levels around 4-6 dS^{-1} (Figure 4-5B (c)). The salinity levels for groundwater users increased significantly, reaching nearly 19 dS.m^{-1} after 18 years when their crops failed. For mixed irrigation users, there was a notable increasing trend over time with some fluctuations, reaching higher EC_e levels towards the end of the iterations, although at a slower rate compared to groundwater users. Those who continue to rely on dam resources maintain relatively stable soil salinity levels throughout the simulation period. Their ECe values remain below 4 dS.m^{-1}.

The initial number of dam users is high, but it declines gradually as more farmers switch to mixed irrigation or cease cultivation (Figure 4-5B (d)). The number of groundwater users starts decreasing after around 9—10 years, corresponding with the rise in soil salinity and decreasing yield. By year 14, almost all groundwater users had ceased cultivation. Mixed irrigation users increase as dam users switch to mixed irrigation to supplement their water supply as the dam fill rate declines. Due to increasing soil salinity from using saline groundwater and reduced availability of dam water impacting the overall productivity, the number of mixed irrigation users stabilised and then decreased as they ceased cultivation.



1 **(A)** **(B)**

Figure 4-5 Changes over 50 iterations under a policy where 15% of annual water abstraction applications are successful, considering theoretical (A) steady and (B) decreasing dam fill scenarios. The subplots present changes in (a) dam fill rates, (b) crop yield, (c) soil salinity levels, and (d) the proportion of agents updating their irrigation strategy. The shaded areas represent the standard errors across 20 simulation runs and their limited visibility reflects the stability of the simulation results.

4.5.2 Sustainability metrics and scenario analysis

In this section, we only consider the following three scenarios: 1) theoretical decreasing dam fill rate, 2) realistic scenario, and 3) climate change scenario.

4.5.2.1 Agricultural productivity

In the theoretical decreasing scenario, the total yield increased as the percentage of authorised water abstractions grew from 0% to around 25% (Figure 4-6). After this point, the yield remained relatively constant, exhibiting minimal change with further increases in water abstraction authorizations. This is indicative that allowing a moderate level of water abstraction expansion boosted the overall total yield. Additional authorisation beyond a certain point resulted in minimal improvements to the total yield.

The realistic scenario showed a very different pattern (Figure 4-6). Total yield declined steadily from the beginning as the percentage of authorised water abstractions increased. The decline was steepest with small increases in water abstraction authorisations but continued at higher authorisation levels.

In the climate change scenario, as the percentage of authorised water abstraction increased from 0% to 2.5%, there was an increase in total yield (Figure 4-6). Then, it began to decline as authorization rose beyond 2.5. This decline was attributable to the balance between groundwater availability and soil salinity levels. Increased water abstraction authorisations initially provided more water for irrigation, but past a certain threshold, the salinity build-up associated with groundwater use negatively impacted crop productivity.

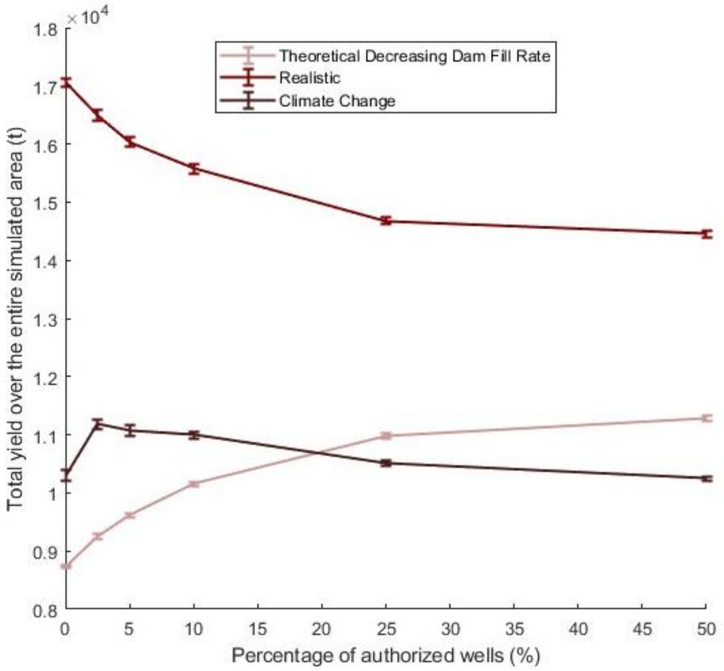


Figure 4-6 Changes in total yield (summed across different irrigation water sources: dam, groundwater and mixed) over the entire simulated area per scenario and policy setting. Error bars represent the standard deviation across 20 simulation runs.

4.5.2.2 Environmental Health

All three scenarios showed a steep increase in the count of agents exceeding the ECe_{50} salinity threshold as the percentage of authorized water abstractions increased, followed by a plateau at higher authorization levels.

For the theoretical decreasing scenario, the initial conversion to mixed irrigation was slow compared to the realistic and climate change scenarios (Figure 4-7 & Figure 4-8). This is because, in this theoretical scenario, the depletion of water resources occurred gradually over time. Unlike the other scenarios, where water scarcity arose more randomly and sporadically, the theoretical scenario presented a more controlled and predictable depletion pattern. As a result, agents had a more extended period to continue cultivation before reaching critical salinity levels.

The realistic scenario demonstrated a steeper increase in the number of farmers exceeding the salinity threshold as more water abstractions were authorised (Figure 4-7). This implied that under realistic conditions, even low levels of water abstraction authorisations can rapidly lead to widespread salinity, and the situation stabilised at a more severe level.

The climate change scenario showed the highest count of farmers exceeding the salinity threshold (Figure 4-7). Climate change exacerbated the impact of water abstraction authorizations on soil salinity due to increased, intensifying reliance on saline groundwater. Consequently, more farmers were pushed beyond the critical salinity threshold, leading to higher rates of land abandonment.

The theoretical scenario, with its gradual resource depletion, showed a slower initial rate of abandonment (Figure 4-8). But, as water scarcity became more pronounced, the rate of abandonment accelerated, mirroring the later stages of the other scenarios. Policies allowing higher water abstraction authorizations led to more rapid and widespread land abandonment, driven by escalating salinity levels and declining agricultural productivity.

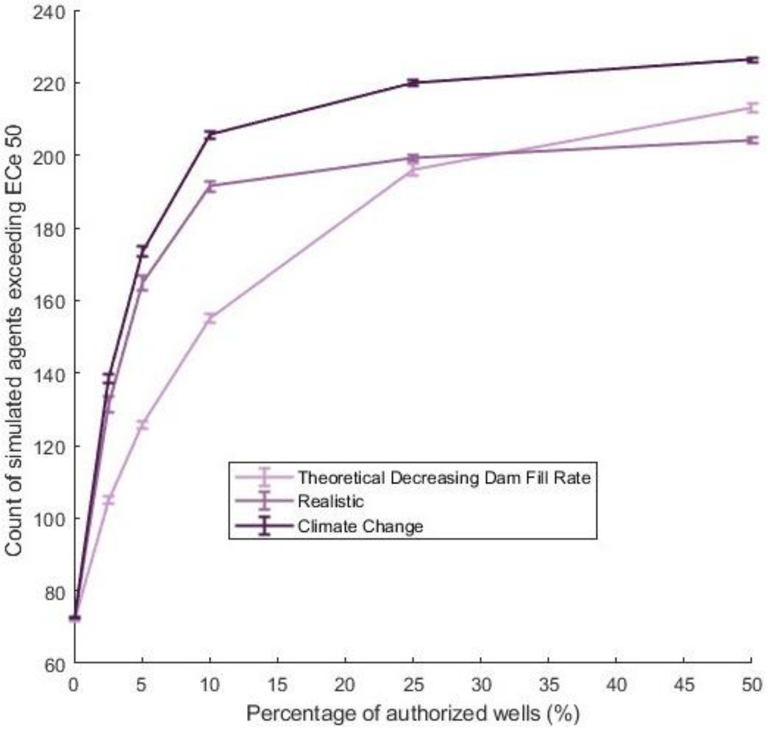


Figure 4-7 Changes in the average count of farmers exceeding the critical soil salinity threshold (ECe_{50}) at which wheat yields are reduced by 50%, under different scenarios (theoretical decreasing, realistic, and climate change) and across a range of water abstraction policies (0-50% of wells authorised). Error bars represent the standard deviation across 20 simulation runs.

4.5.2.3 Social Impact

In the theoretical decreasing scenario, the number of dam water users decreased steadily over time across all water abstraction authorisation percentages (Figure 4-8 (a)). The decline was gradual, with the rate of decline being proportional to the percentage of authorized water abstractions. As water became scarcer and the water abstraction authorization percentage increased, farmers increasingly switched to mixed irrigation to supplement their water supply. This transition was particularly pronounced between 25 to 50% authorization levels. Within this range, the initial decline in dam water users was quite rapid. After the initial steep decrease, the number of dam water users stabilized for a period before experiencing a further decline after 10-12 years. This transition was also reflected in the initial rise of mixed irrigation users, which peaked and then declined as salinity impacts took hold and the water resources continued to deplete. Land abandonment followed a distinct pattern, starting slowly but accelerating as more farmers exceeded the critical soil salinity threshold. For low authorisation scenarios (from 0% to 10%), abandonment was primarily driven by water scarcity, as the rate of abandonment was faster compared to scenarios with a high percentage of water abstraction authorizations. For the latter scenarios, the rate of land abandonment was more or less consistent after 10 years, indicating that soil salinity may have been the primary driver. However, as time progressed, land abandonment steadily increased until sustainable cultivation became unfeasible, due to the combined effects of soil salinity and water scarcity.

In the realistic scenario (Figure 4-8(b)), the number of dam water users decreased more rapidly compared to the theoretical scenario at higher water abstraction authorization percentages but slower at small water abstraction authorisation percentages. The rapid decline in the first case was due to extreme water scarcity conditions arising more randomly, which accelerated the transition to mixed irrigation. Mixed irrigation users initially increased sharply for higher water abstraction authorisation percentages, reaching a higher peak than in the theoretical scenario, as farmers quickly adapted to the diminishing dam water supply. However, the decline in mixed irrigation users also happened more rapidly, reflecting the faster onset of unsustainable conditions due to increased soil salinity. Land abandonment in the realistic scenario exhibited a distinct trajectory compared to the theoretical scenario.

By year 35, under a 50% water abstraction authorization, approximately 64% of farmers (160 out of 248) had abandoned their land in the realistic scenario. In contrast, the theoretical decreasing scenario showed complete land abandonment by all 248 farmers within the same time frame. By year 50 in the realistic scenario, a proportion of farmers remained active, with the percentage of active farmers varying inversely with water abstraction authorization levels. Another significant difference between the two scenarios was the temporal pattern of land abandonment. The realistic scenario displayed a nearly stagnant period of land abandonment between years 15-25, characterized by a flat line in the abandonment curve. Conversely, land abandonment in the theoretical decreasing scenario did not exhibit a period of stagnation progressing continuously over time.

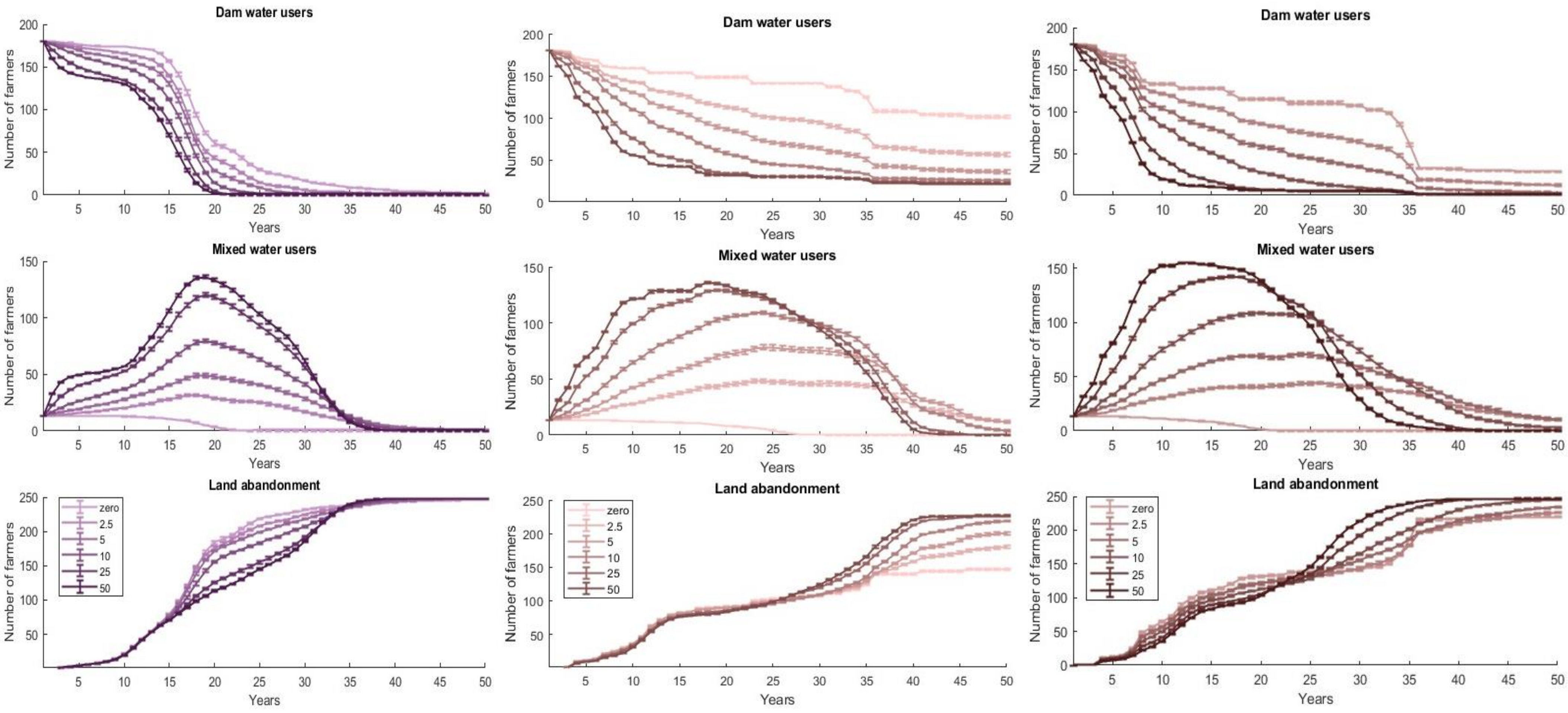
The climate change scenario presented the most severe outcomes (Figure 4-8 (c)). After approximately 10 years, the number of dam water users remained relatively stable for scenarios with 0% and, to a slightly lesser extent for scenarios with 2.5% water abstraction authorization. In contrast with relatively high authorisation percentages (5 to 50%), the number of dam water users decreased sharply, driven by the compounded effects of climate change, forcing a quick transition to mixed irrigation.

Mixed irrigation users experienced a significant initial increase, but this peaked and declined more quickly than in the other scenarios. The impacts of climate change exacerbated soil salinity issues, resulting in mixed irrigation becoming unsustainable in a shorter time frame. Land abandonment was most pronounced in the climate change scenario.

The rapid initial rise and the high plateau of land abandonment reflected the severe conditions under which farmers operated. The high percentage of water abstraction authorizations accelerated the transition to unsustainable practices, leading to a substantial number of farmers abandoning their land early in the iterations. The cumulative effects of climate change drove a higher and faster rate of abandonment compared to the other scenarios.

There is a sharp decrease in the number of active farmers at year 35 in the climate change scenario, which was also evident to a certain extent in the realistic scenario

(Figure 4-8 (b) & Figure 4-8 (c)). This steep decline was particularly prominent for scenarios with 0%, 2.5%, and 5% water abstraction authorization. This is a function of the underlying climate scenario parameters where at around that time farmers experienced episodes of drought. As a result of these severe and recurring drought events, a significant number of farmers reached a critical threshold where cultivation was no longer viable, leading to a rapid increase in land abandonment.



(a) Theoretical decreasing scenario

(b) Realistic scenario

(c) Climate change scenario

Figure 4-8 Changes in the count of different groups of agricultural agents - dam water users, mixed irrigation users, and those abandoning cultivation - over 50 years, as the percentage of authorised water abstractions increases from 0% to 50%. Values shown are averages across 20 simulation realisations.

4.6 Discussion

In this study, we developed an integrated agent-based modelling framework that couples behavioural and biophysical components to investigate the dynamics of shared irrigation water management in an arid agricultural region of Morocco. By modelling heterogeneous farmer decision-making and integrating this with a biophysical model of water availability, soil salinity, and crop productivity, the framework allowed us to investigate the feedback loops between environmental conditions and human management decisions. The scenario analyses conducted provide insights into the potential impacts of policy interventions aimed at regulating groundwater access through water abstraction authorization on the long-term sustainability of the agricultural system

Previous socio-hydrological studies often assume a relatively stable external environment, overlooking the interactions between farmers and the environment (Ghoreishi et al., 2021; Sanderson et al., 2017). In contrast, we explored multiple scenarios and how agents responded to those and those actions in turn affected those environments.

We embedded a biophysical model into the ABM framework and explored multiple climate scenarios and how agents respond to (Figure 4-3). By integrating these components, we gained a more comprehensive understanding of the complex, nonlinear interactions between heterogeneous agents, their environment, and the socio-hydrological system as a whole. This captured the two-way feedback between physical and social processes, a critical aspect of socio-hydrological systems (Di Baldassarre et al., 2015).

Our model allows us to investigate the trade-offs inherent in the management of shared irrigation water resources in arid regions given different policy scenarios. This approach can provide valuable insights into the management of shared irrigation water resources and the potential impacts of various decision-making strategies on the system's sustainability and resilience. In our modelled scenarios, as the percentage of authorized water abstractions increases, the number of farmers abandoning cultivation rises dramatically, particularly under realistic and climate change scenarios (Figure 4-8). This trend suggests that while expanding groundwater access through authorized water abstractions may help maintain or improve yields in the short term, especially when dam water is depleting, the long-term environmental consequences, such as increased soil salinity, can lead to more farmers ultimately exiting agriculture. This finding corroborates studies that have documented the negative impacts of salinization on farm viability and livelihood sustainability in arid regions (Mkilima, 2023; Qadir et al., 2014).

The increasing trend in land abandonment (Figure 4-8), despite the rise in water abstraction authorisations, is a concerning observation that reflects broader sustainability challenges within the modelled agricultural system. This trend highlights the urgent need for the development and implementation of integrated water resource management policies. Such policies consider the long-term availability of both surface and groundwater resources, as well as the socio-economic implications of these resources on the agricultural sector and the wider community.

The rise in land abandonment levels highlights the need for careful consideration of the potential unintended consequences of permissive water abstraction policies. This is consistent with the findings of Malek et al. (2019), who highlight the influence of policy shifts on farmers' land-use decisions, and Reidsma et al. (2018), who stress the importance of incorporating farmer decision-making processes in agricultural policy assessment models to capture potential unintended consequences.

Our results show that in the climate change scenario, there exists an optimum point for water abstraction authorisations (Figure 4-6). This optimum is determined at the catchment scale rather than on an individual basis. By considering the entire catchment, decision-makers can identify a balanced point that maximises yield while ensuring the long-term sustainability of groundwater resources. As shown in Figure 4-6, there is a clear peak in yield outcomes corresponding to a specific level of authorised water abstractions, beyond which yields start to decline due to the overexploitation of groundwater resources. This finding aligns with recent research that emphasizes the importance of integrated water resource management at the catchment level (Dao et al., 2024; Sadath et al., 2023).

Policy-makers must strike a delicate balance between ensuring adequate water access for agricultural productivity and preventing unsustainable groundwater extraction that can lead to soil degradation and eventual land abandonment. This challenge is particularly acute in arid and semi-arid regions, where water scarcity is a persistent concern, and farmers' livelihoods are heavily dependent on reliable access to irrigation water. Policymakers have a range of instruments at their disposal to align individual farmers' incentives with the sustainable use of shared groundwater resources. As highlighted in the literature, the establishment of groundwater extraction quotas can be an effective tool for regulating withdrawals and preventing overexploitation (Grafton et al., 2011; Jakeman et al., 2016). Plus, the lack of comprehensive groundwater monitoring and the focus on surface water resources, as observed in the study region, is a common challenge across many arid and semi-arid areas in Africa.

By setting caps on the volume of groundwater that can be extracted, either at the individual or collective level, these policies create clear boundaries that incentivize more efficient and conservative water use practices among farmers.

Developing integrated policy approaches that combine improved groundwater monitoring and accounting, economic incentives, regulatory frameworks, and meaningful stakeholder engagement will be crucial in navigating this balance (Gleeson & Richter, 2018).

While the data sources are surveys from Morocco, the conceptual modelling framework integrates the TPB, a widely validated theory of human decision-making behaviour. The TPB framework incorporated in this study captures the key constraints and motivations facing farmers who are dependent on variable water resources, a common challenge across arid regions of Africa

(Yazdanpanah et al., 2014). By grounding the agent-based model in the TPB, the factors influencing farmer choices over irrigation source usage have been systematically represented. This approach provides valuable insights that can be translated beyond the specific Moroccan case study, offering a transferable framework for understanding and addressing water management challenges in arid and semi-arid agricultural systems across Africa. Many of these regions face analogous pressures of water scarcity and competing demands for limited water resources (Wada et al., 2010; Wada & Bierkens, 2014).

The integration of behavioural and biophysical components within the ABM framework enabled a nuanced representation of farmer decision-making processes and their interactions with evolving environmental conditions. By parameterizing models behavioural models using survey data and grounding the behavioural component in the TPB framework, the model was able to incorporate key determinants of farmer irrigation choices, such as *attitude* and *PBC*, which have been shown to play a significant role in shaping agricultural water management decisions (El Fartassi et al., 2024).

The ABM approach captured the heterogeneity of irrigation strategies and their underlying drivers, assisting stakeholders and policymakers in designing interventions that better align with the needs and constraints faced by different farmer groups (Voinov & Bousquet, 2010). Consequently, this contributes to developing more equitable and effective water management policies, a key consideration in the context of arid regions where water scarcity exacerbates social and economic vulnerabilities.

4.7 Study Limitations

While the integrated ABM framework developed in this study offers valuable insights into the complex dynamics of shared irrigation water management, it is important to acknowledge several limitations that should be considered when interpreting the findings.

Firstly, as far as possible, we parameterised the model using empirical data, but this was not always possible. Ad hoc choices based on expert knowledge were necessary for certain initial conditions and behavioural parameters. These parameters significantly influenced the rate at which agents respond to changing conditions in the model. Various combinations of initial proportions were explored in preliminary model runs. However, it's important to note that the specific quantitative results may be sensitive to these assumed starting conditions.

Secondly, while the TPB-grounded behavioural component captures a range of socio-psychological factors influencing farmer decision-making, other variables were not accounted for in the current framework. For instance, the model does not explicitly consider the role of extension services, which have been shown to shape agricultural water management practices in some regions (Osumba et al., 2021). Incorporating such additional behavioural determinants could further enhance the model's ability to represent the nuanced decision-making processes of farmers.

Thirdly, the biophysical model simplifies certain hydrological processes, such as the representation of groundwater dynamics and the interactions between surface water and groundwater. In reality, these processes can be highly complex, influenced by factors like aquifer characteristics, recharge rates, and lateral flow patterns, which may vary over space and time. Incorporating more detailed hydrogeological modelling could improve the accuracy of the simulated water availability and quality, particularly in regions with heterogeneous groundwater systems.

Finally, the study focuses on a single crop (wheat) and does not account for potential shifts in cropping patterns that farmers may adopt in response to changing water availability and soil conditions. Expanding the model to include a diverse crop portfolio, along with farmers' adaptive responses in terms of crop selection and management practices, could provide a more comprehensive understanding of the agricultural system's resilience under various policy and environmental scenarios.

Moreover, it is essential to consider that the long-term projections presented in this study are based on current trends and assumptions that do not account for certain dynamic factors. Over a 50-year simulation period, significant technological advances or policy changes may be expected to influence agricultural systems and farmer behaviour, which could mitigate some of the negative impacts observed. For instance, advancements in water-saving technologies, irrigation efficiency, and drought-resistant crop varieties could help stabilize or even reverse the trend of decreasing active farmers (Faures et al., 2007). Additionally, future policy interventions, such as improved access to subsidies or better water management infrastructure, could also positively influence farming viability. Therefore, the model outcomes should be interpreted with caution, considering the uncertainty inherent in projecting socio-economic and technological developments over such extended time scales.

Despite these limitations, the present study serves as a valuable infrastructure for investigating the complex trade-offs inherent in the management of shared irrigation water resources in arid regions. The integrated ABM framework and the insights derived from the scenario analyses can inform the development of more robust and context-specific water governance strategies, while also highlighting the need for further research to address the identified limitations and enhance the model's predictive capabilities.

4.8 Conclusion

The multi-metric ABM framework presented in this study offers a comprehensive, quantitative approach to assessing the sustainability of agricultural water resource use. The model's strengths lay in its ability to represent the heterogeneity of agents, incorporate survey data for parameterisation, and explore multiple climate and policy scenarios. This approach allowed for a more realistic representation of the socio-hydrological system and its inherent complexities. By considering the dynamic interactions between agents, their environment, and the broader socio-hydrological context, the ABM framework contributes to a better understanding of the challenges and opportunities associated with managing shared irrigation water resources in arid regions.

4.9 CRediT authorship contribution statement

Imane El Fartassi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Alice E. Milne:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data Curation, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. **Helen Metcalfe:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Rafiq El Alami:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Alhousseine Diarra:** Software, Formal analysis. **Vasthi Alonso-Chavez:** Validation, Investigation, Writing – review & editing. **Toby W. Waine:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Joanna Zawadzka:** Software, Formal analysis. **Ron Corstanje:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

5 General Discussion

This study aims to explore the benefits of integrating Agent-Based Models (ABMs) of farmer behaviour with biophysical models to describe and understand the complex agroecological systems that influence decision-making in arid and semi-arid regions. The objectives of this thesis are fourfold: first, to characterize the factors influencing farmers' decision-making in Africa through an online survey with farming stakeholders and to identify a case study for in-depth analysis and modelling. Second, to gain a comprehensive understanding of the decision-making processes and contextual factors of farmers in the selected case study. Third, to develop a coupled behavioural-biophysical simulation model that effectively describes the complex agroecological systems that drive decisions in the study area. Finally, use this simulation model to evaluate various scenarios and provide recommendations aimed at enhancing agricultural sustainability in arid and semi-arid regions.

The present chapter assembles and discusses the main findings of the thesis, and concludes by providing potential avenues for future research, aimed at building upon the knowledge gained and addressing any remaining gaps or limitations that have emerged from this work.

5.1 A mixed-methods survey approach to investigate the key factors influencing farmer decision-making in Africa

Agricultural landscape changes manifest as dynamic phenomena resulting from the interaction between the environment and anthropogenic influences. While top-down processes, such as regional policy instruments and market dynamics, play a significant role in shaping landscape patterns, land-management decisions are often made by individual land managers who operate at the local level. These individual choices, when aggregated across a region, contribute to the overall observed landscape patterns and their evolution over time.

Given the inherent complexity and heterogeneity of land manager decision-making processes, we used a combination of analytical and modelling techniques to address the research objectives. In Chapters Two and Three, I describe an application of the use of a mixed-methods survey approach to investigate different facets of farmer decision-making.

In Chapter Two, the use of online surveys provided a platform that facilitated data collection across a wide geographic area of Morocco. By using an online questionnaire, we were able to reach a broad spectrum of farming stakeholders including agronomists, policymakers, and agricultural extension agents. This exploratory approach allowed us to capture differences across the diversity of agricultural practices prevalent in the country and to encompass various agro-climatic zones.

Building on this foundational data collection, our analysis diverged from earlier studies on farmer decision-making that assumed equal importance of all identified influential factors (Piñeiro et al., 2020; Prokopy et al., 2019). Recognizing the inherent heterogeneity of farming communities with their diverse socio-economic, cultural, and environmental contexts (Bartkowski & Bartke, 2018; Dessart et al., 2019) is important as farmers are likely to assign different levels of importance to various factors based on their individual preferences and circumstances (Prokopy et al., 2019; Zeweld et al., 2017). To address this heterogeneity, Chapter Two presents an alternative approach to investigate the factors influencing farmer decision-making, using log-linear modelling to analyse and predict the importance of these factors. The log-linear approach enables the partitioning of individual variable effects and the testing of significant interactions between the factors influencing farmers across different management practices. The survey revealed that, from the perspectives of farming stakeholders, farmer behaviour is not driven by economic incentives alone but is influenced by a combination of factors that tended to cluster around environmental pressures, crop characteristics, and water availability, with water scarcity emerging as a main concern (El Fartassi et al., 2023).

The research focused also on identifying the constraints that impede the adoption of strategies perceived to increase farming resilience. We found that economic constraints are critical in farmers' decisions when considering agricultural innovation adoption. The perceived low profitability or delayed returns on investment for sustainable practices like agroforestry and no-tillage is a significant barrier, especially for smallholder farmers operating on tight margins. This aligns with findings from (Meijer et al., 2015) who emphasize that the economic viability of new practices is often a primary concern for farmers, particularly in developing countries where access to capital is limited. The high investment costs for new technologies and equipment can be prohibitive, especially for smallholder farmers with limited financial resources. This economic barrier extends beyond the initial investment to include the perceived risk of changing established practices that, while perhaps not optimal, are at least predictable and understood.

The reluctance to adopt new practices, especially among older farmers, is a well-documented phenomenon in agricultural innovation studies. (Kariyasa & Dewi, 2013; Paustian et al., 2016; Tey et al., 2014) found that there is often a reluctance to adopt new practices, particularly among older farmers who have decades of experience with traditional methods. This resistance can stem from deeply ingrained cultural norms and a strong sense of identity tied to traditional farming practices. As Ingram et al. (2018) highlight, farmers face various obstacles when considering agricultural innovation adoption, including financial limitations, lack of knowledge, and perceived risks. These barriers can be both real and perceived, often rooted in complex socio-economic and cultural contexts (Meijer et al., 2015).

In my study, I also explored how the acceleration of technology adoption through cooperation could ensure the long-term sustainability of farming. Using a mixed-methods survey approach, I gathered both quantitative and qualitative data on farmers' perceptions of collaborative opportunities. The survey design incorporated specific questions about potential cooperation patterns for different agricultural practices, including agroforestry, no-tillage, irrigation, and fertilizer management. This data revealed how farmers perceive the benefits and challenges of cooperation in these areas, offering insights into the mechanisms that could accelerate the adoption of sustainable practices. I found that the adoption of sustainable agricultural practices can be facilitated through collaborative networks, providing economic incentives, and technical support. Social learning and agricultural technology extension have been identified as effective channels for farmers to obtain technical information and accelerate the adoption of environmentally friendly technologies (Gao et al., 2023). This echoes the work of Schut et al. (2016) who emphasize the importance of participatory approaches that engage farmers, researchers, and policymakers in co-creating solutions. This collaborative approach can help ensure that interventions are tailored to local contexts and address the specific needs and constraints faced by farmers in different regions.

The exploratory online survey conducted in Chapter Two presented a comprehensive overview of the critical challenges confronting agriculture in Morocco, with a particular focus on arid and semi-arid regions. From this initial study, I identified irrigation and water management as critical issues warranting further investigation.

5.2 An in-depth understanding of farmers' decision-making processes in an arid and semi-arid region

The online survey's broad geographic reach across Morocco's varied climatic zones allowed us to capture the heterogeneity of agricultural practices and decision-making processes. While it offered a macro-level perspective, it had limitations in terms of capturing the nuanced behaviour choices of individual farmers. To address this gap, Chapter Three employed in-depth, semi-structured interviews, which provided a more intimate and detailed understanding of the choices farmers make and the constraints and challenges they encounter when considering the adoption of sustainable agricultural practices.

The transition from the broad-scale online survey to the focused interviews allowed us to delve deeper into the specific challenges and decision-making processes related to irrigation in the Al Haouz Basin, Morocco. This approach enabled us to develop a more comprehensive theoretical framework, integrating qualitative findings with quantitative modelling through Structural Equation Modelling (SEM) and the Theory of Planned Behaviour (TPB).

By using the findings from the second Chapter, we were able to design a more targeted and in-depth study that addresses the critical issues of groundwater depletion, drip irrigation adoption, and collective action in water management. This sequential approach demonstrates how initial broader research can inform and guide more focused investigations, which together, lead to a more comprehensive understanding of complex agricultural challenges in arid regions.

Building on this foundation, the open and conversational setting of the interviews in Chapter Three enabled farmer-interviewees to freely articulate their perspectives on the factors influencing their decisions. Instead of guiding participants towards predefined choices, this chapter adopted an inductive approach, allowing for the exploration of emergent themes. It facilitated the emergence of issues that were not captured in the online surveys, such as land tenure limitations and policy constraints that hindered the uptake of sustainable practices.

We found that land tenure emerged as a critical factor influencing farmers' decisions with land ownership conferring greater long-term perceived control over sustainable resource management compared to tenancy arrangements. Responses indicated land tenure insecurity discouraged investments in sustainable practices such as drip irrigation installation, which require upfront costs and yield benefits over extended periods. This aligns with findings by Salmerón-Manzano & Manzano-Agugliaro (2023) and Sugden (2014) who observed that insecure tenure contributes to a cycle of food insecurity, limited economic opportunities, and persistent poverty. While some studies show positive links between improved tenure security and sustainable outcomes such as higher per-hectare yield, income, profit and technical efficiency (Mazhar et al., 2023), conflicting evidence exists. For instance, Huntington & Shenoy (2021) found that a land certification program in Zambia had no impact on investment, challenging the consensus that tenure insecurity deters investment in sustainable practices. The conflicting evidence regarding the impact of tenure security on sustainable outcomes can be attributed to several contextual and systemic factors. One possible reason is the variability in socio-economic conditions across different regions. For instance, in contexts with significant constraints, such as limited access to credit, inadequate infrastructure, or volatile markets, improved tenure security alone may not drive investment. Studies have shown that access to complementary resources, such as financial services, plays a critical role in translating tenure security into productive investments (Deininger et al., 2011). Without these, farmers may be unable to fully capitalise on the benefits of tenure security.

Another factor is the design and implementation of land tenure programmes. Programmes that fail to address broader institutional challenges, such as weak enforcement of land rights, corruption, or inequitable access to land, may have limited effectiveness. Evidence from African land certification programmes highlights that poorly implemented initiatives often fail to instil sufficient trust and confidence in landowners, undermining their willingness to make long-term investments (Place, 2009; Toulmin, 2009).

Furthermore, the distinction between formal and perceived tenure security is crucial. Farmers may feel secure under customary arrangements in regions where informal systems are trusted and stable, rendering formal certification redundant (Besley, 1995). Conversely, formal certification may not address the underlying causes of tenure insecurity in areas with weak governance or ambiguous legal frameworks, leading to limited behavioural changes (Fenske, 2011).

One of the key policy constraints we identified is the paradoxical promotion of drip irrigation alongside efforts to limit groundwater use. We note that without reliable access to water sources, particularly groundwater through wells, farmers are unable to install drip irrigation systems. This dependency on well access creates a significant barrier to the adoption of drip irrigation, especially in areas where groundwater resources are limited or where there are restrictions on water abstractions. As Molle & Tanouti (2017) note, government incentives aimed at encouraging drip irrigation adoption for increased productivity and water savings have inadvertently led to increased groundwater extraction. This phenomenon can indeed be interpreted as an example of Jevon’s Paradox, where improvements in technological efficiency lead to greater, rather than reduced, resource consumption. In this case, while drip irrigation is more water-efficient at the field scale, the resulting increases in productivity and profitability often incentivise farmers to expand irrigated areas or intensify production, thereby offsetting any potential water savings (Kuper et al., 2018). This policy contradiction highlights the complexity of achieving resource conservation through technological innovation alone. It highlights the need for complementary governance measures, such as limits on groundwater extraction or incentives for conserving water, to ensure that efficiency gains translate into sustainable resource use rather than exacerbating resource depletion. This interconnection points to the need for policies that not only promote efficient irrigation technologies but also address equitable access to water resources and sustainable groundwater management. As Foster & Garduño (2013) argue, effective groundwater governance requires an integrated approach that balances technological innovation with resource conservation and social equity.

Overall this study showed a wide range of factors influencing farmer decisions that related to *attitude* and *Perceived Behavioural Control (PBC)*. The complex bureaucratic policy framework related to securing subsidies to acquire irrigation technologies created confusion and disincentives for farmers This finding is consistent with the findings of Sidibé et al. (2018) in their study of irrigation technology adoption in Burkina Faso. They noted that while subsidies can potentially encourage adoption, the bureaucratic hurdles and lack of clear information often negate their intended benefits, particularly for smallholder farmers. The issue of policy-induced confusion and disincentives also resonates with research by Zeweld et al. (2017) in Ethiopia. Their study on the adoption of sustainable agricultural practices found that overly complex policy frameworks and unclear subsidy mechanisms can discourage farmers from adopting new technologies, even when those technologies could significantly improve their productivity and sustainability. In the context of drip irrigation specifically, Venot et al. (2014) observed in their multi-country study that the effectiveness of subsidy programs for drip irrigation is often compromised by bureaucratic inefficiencies and a lack of coordination between different governmental agencies. This fragmentation in policy implementation creates confusion among farmers and limits the reach and impact of such programs.

These findings collectively stress the need for policy frameworks that not only provide financial incentives but also ensure clear, accessible pathways for farmers to benefit from these incentives. As Merrey & Lefore (2018) demonstrate, effective promotion of irrigation technologies requires not just subsidies, but also institutional support, clear communication, and simplified procedures that are responsive to farmers' needs and capacities.

The observed propensity to adopt drip Irrigation could be attributed to financial benefits or awareness of sustainability. However, we could not conclude with certainty whether this shift is a genuine behavioural change towards environmental stewardship, reflecting environmental consciousness among the participants or an opportunistic reaction to the financial incentives and increased productivity that drip irrigation offers. The long-term sustainability of this adoption trend may be disproportionately reliant on existing financial stimuli, raising concerns about the trajectory of adoption should these economic incentives diminish or cease. In their study of climate-smart agriculture adoption in Zimbabwe, Mango et al. (2018) found that while economic factors were primary drivers, environmental considerations also played a role in farmers' decision-making processes. However, they noted the difficulty in distinguishing between genuine environmental stewardship and economically motivated actions. This uncertainty echoes observations by Nigussie et al. (2017) in Ethiopia and indicated that while financial incentives often drive initial adoption, long-term maintenance of sustainable practices requires intrinsic motivation and environmental consciousness. A study by Van Ittersum et al. (2016) examined the challenges of sustainable intensification in sub-Saharan Africa. They found that increased agricultural efficiency often led to expanded cultivation areas, potentially offsetting environmental benefits. This highlights the complex relationship between technology adoption, economic incentives, and environmental outcomes in African agriculture.

To enhance farmers' resilience, especially in climate-sensitive areas, policymakers must develop targeted, comprehensive policies and interventions that support the adoption of sustainable, climate-resilient agricultural practices. Bryan et al. (2013), studying climate change adaptation in Africa, emphasizes the importance of policies that address multiple barriers simultaneously, including financial, technical, and institutional constraints. This is particularly critical for risk-averse farmers with uncertain land tenure.

The combination of online surveys and in-depth interviews in Chapters Two and Three allowed for a multi-scalar analysis of farmer behaviour and decision-making. While the online surveys provided a broad overview of the factors influencing farming decisions across diverse agro-climatic zones, the interviews offered a more granular and contextual understanding of farmers' constraints and barriers to adopting sustainable practices. For instance, in Chapter Two, we found farm size as one of many factors influencing farmers' behaviour but did not deeply explore its impact. In Chapter Three, we place significant emphasis on how farm size and land tenure influence decision-making and the ability to adopt sustainable practices. These complementary approaches yielded a rich and comprehensive picture of the complex interaction between individual, institutional, and environmental factors shaping agricultural sustainability in Morocco. In Chapter Two, we found that the adoption of drip irrigation was significantly influenced by subsidies, which in turn prompted changes in crop choice. This demonstrates how subsidies not only induced an adjustment in farmers' behaviour shifting from surface to drip irrigation but also influenced crop choices. In our third chapter, we elaborated on this trend, and we found that large-scale farmers were particularly responsive with a clear transition towards olive cultivation. This shift is linked to the adoption of drip irrigation systems, as olives can be efficiently grown with precise water application. While acknowledging the role of subsidies in promoting drip irrigation in Chapter Two, we highlighted in Chapter Thee how the complexity of subsidy applications can deter adoption, particularly for small-scale farmers who may lack the resources or knowledge to navigate the application process.

The study also contributes to our understanding of the temporal dynamics of adaptation. It captures how farmers' strategies evolve in response to changing environmental conditions, policy landscapes, and socio-economic factors. The research reveals a spectrum of responses ranging from short-term coping mechanisms to long-term transformative adaptations. For instance, I identified immediate responses such as reducing cultivated areas or increasing reliance on groundwater pumping as short-term strategies. These contrast with more substantial adaptations like transitioning to drought-resistant crops or adopting water-efficient irrigation technologies, which represent longer-term strategic shifts. This temporal perspective contributes to the theoretical framework of climate change adaptation in agriculture by understanding the long-term trajectory of agricultural systems under climate change.

We translated the factors influencing decision-making processes regarding irrigation management practices to an integrative theoretical modelling approach, combining the TPB and SEM. The TPB enabled modelling of how *attitude*, *subjective norms*, and *PBC* influenced *intentions* to use groundwater and drip irrigation adoption *behaviour*. By combining the TPB with SEM, I quantified and analysed the relationships among these constructs. I found that farmers' *attitude* and *PBC* strongly influenced their *intention* to use groundwater and drip irrigation adoption *behaviour*. Specifically, *attitude* toward the efficiency of drip irrigation and the salinity levels of groundwater shaped farmers' *intentions* to use groundwater. Unexpectedly, concerns about groundwater scarcity did not significantly impact *attitude*. Moreover, the common apprehension over salinity negatively affected *attitude* but did not translate into reduced usage. This highlighted farmers' continuous preference for groundwater, driven by subsidies for drip irrigation and the enhanced productivity it enabled. These findings are consistent with prior studies. Boularbah et al. (2019) and Kuper et al. (2018) that in collective irrigation systems where water resources are scarce and unpredictable, there is a tendency towards groundwater overexploitation.

In the context of farming and environmental management, applying the TPB to agricultural water management provides a more comprehensive understanding of what motivates farmer decision-making compared with more rational theories. It helped explain why farmers might adopt (or resist) certain practices, even when they seem objectively beneficial. I found that small-scale farmers, in particular, perceived significant barriers to accessing grants for drip irrigation, regardless of the actual availability of such support. This finding is consistent with Kurgat et al. (2018) in their study of drivers of sustainable intensification in Kenya. They found that perceived difficulties in accessing agricultural subsidies and support significantly hindered the adoption of climate-smart agriculture practices like drip irrigation. They noted that even when support programs were available, small-scale farmers often perceived them as inaccessible due to complex application processes or lack of information.

I also found that *subjective norms* exerted a lesser impact on farmers' *intentions* compared to *attitude* and *PBC*. Although *subjective norms* may not directly impact *intention*, their influence was offset by the inherent positive correlation with *attitude* and *PBC*, thereby reinforcing their role in shaping *intentions.*

The research findings have significant practical implications offering tangible pathways for improving sustainable water management and agricultural resilience. They provide an understanding of the diverse factors that influence farmer decision-making, which equips policymakers with a better understanding of the complex motivations and constraints that shape farmers' choices. My findings highlight the need for policymakers to tailor interventions that address the specific needs and motivations of different farmer groups, rather than implementing one-size-fits-all solutions. Plus, the research reveals that farmers' decisions are influenced not just by economic factors, but also by attitudes and PBC. This implies that effective policies need to address multiple dimensions of farmer behaviour, rather than focusing solely on economic incentives.

The identification of land tenure issues as a significant barrier, for instance, suggests that policies addressing land rights and tenure security could promote long-term investments in sustainable water management. Similarly, the finding that subsidy application complexities deter adoption, especially among smaller farmers, points to the need for simplifying administrative processes or providing support for navigating these procedures. These observations support policymakers and program designers to focus their efforts on the most significant obstacles, potentially increasing the effectiveness and efficiency of interventions.

5.3 Developing a coupled behavioural-biophysical simulation model for agricultural decision-making in arid and semi-arid ecosystems

Although the approach above explains farmer decisions to a large extent, it is imperative to recognize that farmers are not homogeneous. While acknowledging the heterogeneity associated with individual farmers' decision-making for understanding landscape dynamics and emergent patterns, inaccurate or overly detailed descriptions of each farmer description can lead to an excessive amount of data. In such instances, organising this heterogeneity for agent-based modelling parameterization and policy analysis is imperative.

A generic approach used to categorize the inherent diversity within farming communities is the development of typologies. In the context of this thesis, farmer typology profiles were clustered based on farm size and tenure. The behavioural component of my ABM was informed by the survey data and analysis presented in Chapter Three, where I used SEM underpinned by the TPB to identify the most significant factors influencing farmers' irrigation source decisions. The factors influencing farmer behaviour formed the basis of the classification criteria. They comprised two primary components: *attitude* and *PBC*. The *attitude* was primarily influenced by crop yield contingent upon water supply and soil salinity levels. On the other hand, PBC was determined by affordability and operational constraints, which are closely linked to farm size and ownership structure. This empirical grounding lent robustness to our model and ensured it captures the key determinants of farmer behaviour.

In developing the behavioural component, we also drew upon several key concepts from behavioural economics and social psychology. The model incorporated elements of “economies of scale” to represent how farm size influences the affordability of groundwater extraction. This approach aligns with research by Michael (2009), which highlights the importance of farm size in determining production efficiency and economic viability. We implemented this by assigning different initial affordability values to agents based on their farm size classification (small, medium, or large), reflecting the assumption that larger-scale farmers generally have higher affordability for investing in groundwater extraction infrastructure. Additionally, we used opinion dynamics models to capture the varying opinions across the agents, social influence and information exchange processes that shape farmers' PBC over time. This approach allowed us to simulate how farmers' perceptions and decisions are influenced by their interactions with other farmers, particularly those of similar farm sizes. It also enabled us to account for the relative perception of influencing factors rather than their absolute importance, reflecting the understanding that farmers perceive opportunities and constraints differently based on their individual circumstances and social context (Wuepper et al., 2018). This approach aligns with the work of Mwangi & Kariuki (2015) in their comprehensive review of factors influencing the adoption of agricultural technology in developing countries. They emphasize that farmers' perceptions of technology attributes and their relative importance vary significantly based on socioeconomic factors, farm characteristics, and institutional contexts. My research extends this understanding by explicitly accounting for these relative perceptions in the context of irrigation technology adoption.

The integration of empirical data from surveys and interviews with theoretical frameworks such as SEM and the TPB highlights the potential for bridging disciplinary boundaries and creating more robust ABMs. Schlüter et al. (2017), in their comprehensive review of modelling approaches in social-ecological systems research, emphasize the need for integrating empirical data with theoretical frameworks to improve the predictive power of ABMs. They specifically call for more research that combines qualitative and quantitative data collection methods with behavioural theories to better represent human decision-making in complex systems. Similarly, Müller et al., (2013) encourage the inclusion of empirical data and theoretical justifications in model design, which helps in building credible and ABM robust models. The call for multidisciplinary research is further echoed by van Wijk et al. (2014) in their review of farm household models for poverty impact analysis. They emphasize the need for models that incorporate both empirical data on farmer behaviour and theoretical frameworks explaining decision-making processes, particularly in the context of smallholder agriculture in Africa.

The research demonstrates several methodological innovations that enhance the study of agricultural systems. The novel integration of qualitative and quantitative methods, combining online survey data, in-depth interviews, SEMs and ABMS, provides a robust methodological framework for studying complex socio-ecological systems.

5.4 An agent-based simulation model of farmer decision-making in Arid and semi-arid ecosystem

The ABM modelling framework developed enabled us to explore scenarios that were beyond the scope of the initial survey-based study. For instance, we simulated the long-term impacts of different water abstraction authorization policies under various climate scenarios. It allowed us to investigate the potential unintended consequences of policies aimed at increasing agricultural productivity, such as the risk of increased soil salinization and land abandonment.

In our modelled scenarios, as the percentage of water abstraction authorizations increased, the number of farmers abandoning cultivation rose dramatically, particularly under realistic and climate change scenarios. These findings suggest that while expanding groundwater access through water abstraction authorizations may provide short-term benefits, it can lead to long-term environmental consequences, particularly increased soil salinity. Pavelic et al. (2013) highlight how the uncontrolled expansion of groundwater use in Sub-Saharan Africa can lead to aquifer depletion and water quality degradation, mirroring our simulation. Our results extend this understanding by demonstrating that even regulated expansion through water abstraction authorizations can produce similar long-term environmental consequences if not carefully managed. In Ethiopia, Mosello et al. (2015) found that expanding irrigation through groundwater development, while aimed at improving food security and livelihoods, led to increased competition for water resources and social tensions. This parallels our simulation outputs of farmers abandoning cultivation, suggesting that increased access to groundwater can paradoxically lead to decreased agricultural activity over time. Similarly, Villholth et al. (2013) identified risks of overexploitation and inequitable access in Southern African countries, further corroborating the potential for unintended consequences in groundwater development initiatives. Parameterizing the model with data from Chapter Three also sets a sound foundation for model predictions. Ultimately, the model's ability to inform a policy for granting water abstraction authorizations under climate change scenarios is a significant contribution.

This demonstrates the potential of such integrated modelling approaches to predict the outcomes of policies before they are implemented. The model provides a pragmatic starting point for policy decision-making that should be updated and informed through additional data collection on the response of soil health and productivity to groundwater use. This data can be used to update the model predictions providing a useful tool for policymakers to assess potential changes and their effects on both the environment and agricultural productivity. Integrated modelling approaches have been highlighted as a useful approach to help evaluate the system performance under different scenarios, balancing the competing needs and objectives. A study by Giuliani et al. (2016), employed multi-objective optimization models to evaluate trade-offs between conflicting water management objectives, providing policymakers with tools to anticipate potential conflicts. Similarly, Jakeman et al. (2016) recognise that groundwater issues are interconnected with socioeconomic and environmental factors, making it crucial to address these aspects jointly. This integrated modelling approach represents a significant advancement in socio-hydrological modelling by combining empirically grounded behavioural models with biophysical processes, leading to contextually relevant simulations. This integration captured the complex feedback between human decision-making and environmental processes and enabled the exploration of emergent phenomena and long-term dynamics that might not be visible in static data analysis alone.

This research also has important implications for cooperative management strategies. By highlighting both the potential for and challenges of cooperative approaches to water management, the study informs the development of community-based resource governance models. The findings suggest that while there is often a low propensity for cooperation among farmers, there are opportunities to foster collective action through appropriate institutional arrangements and incentives. For instance, the research highlights the need to design collective management institutions and address issues of trust, equity, and shared benefits. It could guide the development of cooperative irrigation schemes that balance individual and collective interests and inform the creation of platforms for knowledge sharing and collective decision-making among farmers.

The findings from this study, while focused on a specific region, have global implications. Many of the challenges addressed, such as water scarcity, resource overexploitation, and the need for sustainable practices, are universal issues that many regions worldwide are facing. Thus, the research can inform global efforts towards achieving sustainable development goals.

5.5 Limitations and further research

The ABM framework developed in this study enabled the simulation of long-term agricultural system dynamics under various scenarios, effectively capturing the complex feedback loops between human decision-making and environmental processes. However, the accuracy of these long-term projections remains inherently uncertain, particularly given the complexity of climate systems and the potential for technological or socio-economic changes that could alter the trajectory of agricultural systems. It is also important to acknowledge that different models serve different purposes. Predictive models, such as process-based biophysical models, are primarily used to generate specific forecasts of future system states, often requiring highly precise and validated parameters (Seppelt et al., 2013). On the other hand, conceptual or exploratory models, such as system dynamics models or agent-based models, aim to improve qualitative understanding of system behaviour and interactions rather than provide precise predictions. The ABM in this study falls into this latter category, focusing on elucidating the key dynamics and feedback mechanisms within agricultural systems rather than achieving precise long-term forecasts. By enhancing understanding of the complex feedback mechanisms and potential emergent behaviours, these models contribute to formulating adaptive and informed policy decisions, even in the face of uncertainty (Janssen & Ostrom, 2006). The models' predictive power may decrease over longer time horizons. Additionally, the current models focus primarily on water availability and soil salinity but may not capture other important long-term factors such as biodiversity loss, pest dynamics, or market changes.

To enhance the policy relevance and long-term utility of these models, it is crucial to implement a system of continuous monitoring and model updating. This approach, akin to Model-View-Controller architecture in software development (Leff & Rayfield, 2001), would involve regular on-site monitoring of key indicators such as soil salinity levels, crop yields, water table depths, and biodiversity metrics. This data would serve as a feedback mechanism for the model, allowing for periodic recalibration of model parameters and assumptions to ensure alignment with evolving environmental and socio-economic conditions. The implementation of this continuous monitoring and updating system would significantly enhance the long-term usefulness of the ABM framework for policy-making. The dynamic feedback mechanism would allow for the development of an adaptive policy framework that can be adjusted based on insights gained from the continuously updated model. Such an approach facilitates early detection of unintended consequences or emerging issues, validation and improvement of model predictions over time, and adaptive management of agricultural systems in response to changing conditions.

This system would benefit greatly from regular engagement with stakeholders, including farmers, policymakers, and other relevant parties. Through workshops, forums, or other participatory methods, these stakeholders' observations and experiences can be incorporated into the model refinement process. As new challenges or opportunities arise, such as the introduction of new irrigation technologies or changing market demands, the model can be expanded to include these factors, maintaining its relevance over time.

By implementing such a system, the ABM framework transitions from a static predictive tool to a dynamic decision support system. This evolution not only improves the accuracy and reliability of the model over time but also ensures its continued relevance in guiding sustainable agricultural water management policies.

While incorporating additional complexity into the ABM framework may contradict the concept of models as a simplified and abstract representation of reality, integrating additional features could potentially improve the results of the simulations.

The methodologies developed in this research, including the integration of the TPB with SEM and ABM, could be applied to other arid and semi-arid regions for comparative analyses. This could help identify common patterns and region-specific factors influencing agricultural water management and adaptation strategies. A limitation here is that the current study is heavily contextualized to the specific socio-economic and environmental conditions of the study area in Morocco. Applying these methodologies to other regions would require adaptation and re-parameterization of the models. The transferability of the findings to regions with different cultural, economic, or institutional contexts may be limited due to several factors. Firstly, cultural norms and social dynamics can vary widely between regions, significantly impacting farmers' attitudes towards cooperation, technology adoption, and resource use (Adger et al., 2009). These factors influence decision-making processes, especially in collective management settings or when adopting new agricultural technologies. Economically, differences in the availability of subsidies, access to credit, and the general economic environment can affect farmers’ ability to adopt new practices and technologies. For example, regions with limited access to financial support may face constraints that make the adoption of new irrigation techniques less feasible (Pahl-Wostl et al., 2010). Institutionally, the governance frameworks that regulate water resources, land use, and agricultural practices can vary significantly. Different policy environments lead to distinct regulatory constraints or incentives, affecting how effectively agricultural and water management strategies can be implemented across regions (Seppelt et al., 2013). These factors mean that the core model structure may need significant adjustments to capture regional variations, as the drivers influencing farmer behaviour and system dynamics are highly context-dependent.

Therefore, while the fundamental concepts and methodological approach of the model can be adapted, its direct extrapolation without substantial modifications is not recommended due to these critical differences in socio-economic, cultural, and institutional contexts. Furthermore, the data collection methods, particularly the reliance on surveys and interviews, may need to be adjusted for different cultural contexts.

The ABM developed in this research offers a promising tool for testing the potential impacts of different policy interventions. It provides a platform to simulate the effects of various policy scenarios. This capability makes the ABM a valuable asset for policymakers and researchers seeking to understand the complex dynamics of agricultural systems and the potential consequences of policy decisions. However, there are limitations and challenges associated with this approach. The model's ability to accurately predict policy impacts is fundamentally dependent on the accuracy of its underlying assumptions and parameters. While efforts were made to parameterize the model using empirical data wherever possible, this was not always feasible. The structure of the behavioural model was validated through statistical analysis of the semi-structured interview data, ensuring a strong empirical foundation for the agent decision-making processes. However, for certain initial conditions and behavioural parameters, ad hoc choices based on expert knowledge were necessary. These parameters significantly influenced the rate at which agents respond to changing conditions in the model. Various combinations of initial proportions were explored in preliminary model runs. However, it's important to note that the specific quantitative results may be sensitive to these assumed starting conditions.

The complexity of real-world policy implementation presents another challenge. The model may not capture all relevant factors or interactions that influence policy outcomes in actual agricultural systems. The current focus on water management policies, while valuable, may not adequately represent the impacts of broader agricultural or economic policies that could significantly affect farmer decision-making and system dynamics. To address this limitation, efforts were made to engage stakeholders and incorporate their feedback into the model evaluation process. A workshop was conducted with local stakeholders, as reported in the Appendix, to gather insights on potential missing factors and to validate the model's outputs against real-world observations. While time constraints and pandemic-related challenges limited the scope of this stakeholder engagement, the workshop provided valuable feedback that could inform future model refinements.

Despite these limitations, the ABM remains a valuable tool for policy analysis. It provides a structured framework for exploring potential policy impacts and understanding the complex interactions between policy interventions, farmer behaviour, and environmental outcomes. However, results should be interpreted with caution, understanding that they represent possible scenarios rather than definitive predictions.

To enhance the model's utility for policy analysis, future research could focus on refining parameter estimates through more extensive data collection, conducting sensitivity analyses to understand the impact of uncertain parameters, and expanding the model to incorporate a broader range of policy types and their interactions. Additionally, validation against real-world policy implementations, where possible, could further strengthen the model's credibility for policy analysis.

6 Conclusions

The research presented in this thesis aimed to understand the benefits of integrating Agent-Based Models (ABMs) of farmer behaviour with biophysical models to describe and understand complex agroecological systems driving decisions in arid and semi-arid regions. Through a multi-method approach combining online surveys, in-depth interviews, and agent-based modelling, this study has uncovered key determinants influencing farmer decision-making and evaluated the potential impacts of various management strategies on agricultural sustainability.

The initial stages of the research employed online surveys to gather data from a diverse range of farming stakeholders across Morocco. This approach allowed for a broad assessment of the factors influencing farming decisions across various agro-climatic zones. The analysis of this data using log-linear modelling revealed that farmer behaviour is influenced by a complex interaction of factors, including environmental pressures, crop characteristics, and water availability.

Building upon these findings, the research thoroughly explored the specific challenges faced by farmers in the Al Haouz Basin, Morocco, through in-depth, semi-structured interviews, focusing on water management as a main case study. This approach provided a more granular understanding of the constraints and barriers to adopting sustainable agricultural practices. The interviews revealed that farmers often face institutional barriers, such as land tenure insecurity and complex bureaucratic processes, which can discourage investments in sustainable practices like drip irrigation. These insights highlight the necessity for policymakers to develop targeted, comprehensive interventions that address both the economic and institutional barriers to sustainable agriculture.

The integration of empirical data with theoretical frameworks such as Structural Equation Modelling (SEM) and the Theory of Planned Behaviour (TPB) represents a significant methodological advancement in this research. This approach allowed for a more robust parameterization of the ABM, ensuring that the simulated farmer behaviour was grounded in empirical observations and established psychological theory. The use of SEM in conjunction with TPB provided a quantitative understanding of the relationships between various factors influencing farmer behaviour.

The development of a coupled behavioural-biophysical simulation model represents the culmination of this research. This integrated approach captured the complex feedback loops between environmental conditions and human decisions, providing a more comprehensive view of the challenges facing agricultural water management in water-scarce regions. The model's ability to simulate the long-term impacts of different water abstraction authorizations revealed important insights into the potential unintended consequences of policies aimed at increasing agricultural productivity. For instance, the model showed that as the percentage of authorized abstraction increased, there was a significant rise in the number of farmers abandoning cultivation, particularly under realistic and climate change scenarios. This finding suggests that while expanding groundwater access through authorized water abstraction may provide short-term benefits, it can lead to long-term environmental consequences, particularly increased soil salinity.

The research presented in this thesis makes several significant contributions to the field of agricultural water management and sustainable farming in arid and semi-arid regions. Theoretically, it advances our understanding of the temporal dynamics of adaptation, demonstrating how farmers' strategies evolve in response to changing environmental conditions, policy landscapes, and socio-economic factors. This temporal perspective contributes to the theoretical framework of climate change adaptation in agriculture by elucidating the long-term trajectory of agricultural systems under climate change.

Methodologically, the novel integration of qualitative and quantitative methods, combining online survey data, in-depth interviews, and ABM, provides an innovative framework for studying complex socio-ecological systems. The development of a comprehensive ABM that incorporated both behavioural and biophysical components represents a significant innovation, offering a powerful tool for simulating the long-term dynamics of agricultural systems under different scenarios.

Practically, a detailed understanding of the diverse factors influencing farmer decision-making equips policymakers with the knowledge to design more effective, tailored interventions and importantly how it is delivered. The identification of specific barriers to the adoption of sustainable practices, such as land tenure issues and subsidy application complexities, provides clear targets for policy reform. The scenario analyses conducted using the ABM offer a valuable tool for long-term planning, allowing decision-makers to anticipate potential outcomes and challenges under different climate, policy, and management scenarios.

By bridging the gap between social and natural sciences through the integration of behavioural components into biophysical models, the research provides a comprehensive methodological framework for addressing the complex challenges facing agricultural sustainability.

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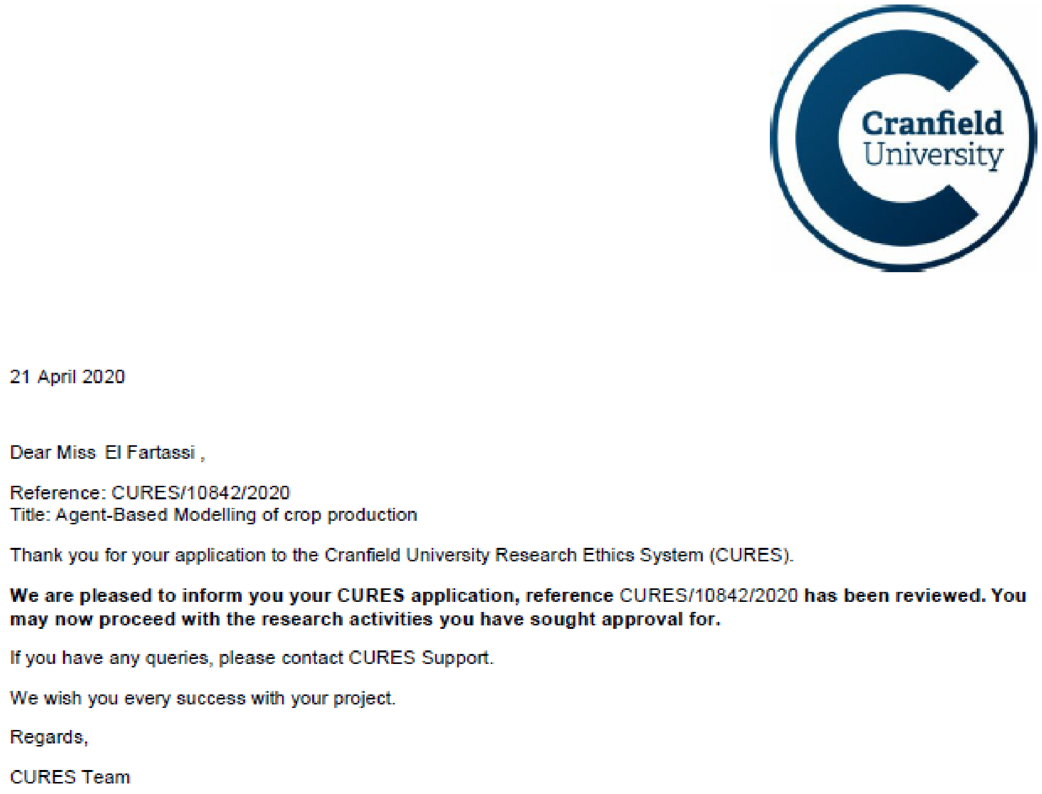
8 Appendices

Appendix A Ethical approval letter



21 April 2020

Dear Miss El Fartassi ,

Reference: CURES/10842/2020
Title: Agent-Based Modelling of crop production

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/10842/2020 **has been reviewed. You may now proceed with the research activities you have sought approval for.**

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Supplementary material for Chapter Two

B.1 Survey questions

B.1.1 General background

Question 1.1: Surname. Text entry.

Question 1.2: First name. Text entry.

Question 1.3: Email address. Text entry.

Question 1.4: Which category below includes your age? Answer selected from the following responses: A) 18 – 24; B) 18 – 24; C) 35 – 44; D) 45 – 54; E) Above 55.

Question 1.5: What is your gender? Answer selected from the following responses: A) Male; B) Female.

Question 1.6: What is the highest degree or level of education you have completed? Answer selected from the following responses: A) Technician diploma; B) Bachelor's degree; C) Master's degree; D) Engineering degree; E) PhD or higher; F) Other.

Question 1.7a: What is your occupation? A) Agronomist; B) Agronomist developer; C) Agronomist consultant; D) Agronomist adviser; E) other.

Question 1.7b: If other, please specify. Text entry.

Question 1.8: Years of field experience. Answer selected from the following responses: A) 0-5; B) 5-10; C) Above 10.

Question 1.9: What does your current headquarter area? Answer selected from the following responses: A) Tanger-Tétouan-Al Hoceïma; B) L'Oriental; C) Fès-Meknès; D) Rabat-Salé-Kénitra; E) Béni Mellal-Khénifra; F) Casablanca-Settat; G) Marrakech-Safi; H) Drâa-Tafilalet; I) Souss-Massa; J) Guelmim-Oued Noun; K) Laâyoune-Sakia El Hamra; L) Dakhla-Oued Ed Dahab.

B.1.2 Crop choices

Question 2.1: To what extent do the following environmental factors influence the choice of crops? Respondents were asked to evaluate the contribution of 4 factors: A)

Climate; B) Soil and land characteristics; C) Water availability; D) Previous crop; via a Likert scale with 3 points that range from not important, to very important.

Question 2.2: To what extent do the following economic factors influence the choice of crops? Respondents were asked to evaluate the contribution of 6 factors: A) Subsidies and grants; B) Labour availability; C) Capacity and readiness to invest; D) Contract with industries; E) Crop insurance; F) Profitability via a Likert-scale with 3 points that range from not important, to very important.

Question 2.3: To what extent do the following social factors influence the choice of crops? Respondents were asked to evaluate the contribution of 3 factors: A) Prior experience with the crop; B) Passed down through the generations; C) Education; via a Likert scale with 3 points that range from not important, to very important.

Question 2.4: To what extent do the following “crop characteristics” factors influence the choice of crops? Respondents were asked to evaluate the contribution of 5 factors: A) Resistance to pests and diseases; B) Drought resistance; C) Maturity dates; D) High yield; E) Length of the growing season; via a Likert scale with 3 points that ranges from not important, to very important.

Question 2.5: To what extent do the following “farm size and facilities” factors influence the choice of crops? Respondents were asked to evaluate the contribution of 4 factors: A) Farming system; B) Availability of machinery and maintenance facilities; C) Storage facility or accessibility; D) Technology; via a Likert-scale with 3 points that ranges from not important, to very important.

Question 2.6: Have you noticed any behavioural persistence or slow adoption of agroforestry? Answer Yes or No.

Question 2.7: If yes expand, if not, why do you think so? Text entry.

Question 2.8: In your opinion, are there opportunities to improve agroforestry adoption through collaboration networks or co-creation plans? Answer Yes or No.

Question 2.9: If yes expand, if not, why do you think so? Text entry.

B.1.3 Tillage practices

Question 3.1: Rank the following tillage systems according to how commonly they are used in your area from 1 (most common) to 3 (least common). Answer selected from the following three responses: A) Conventional tillage; B) Reduced tillage; C) No-tillage.

To identify what factors most likely drive farmers' decision to adopt a tillage system, we asked respondents to evaluate the contribution of seven factors to the implementation of conventional tillage, reduced tillage, and no-till via a Likert scale with 3 points that range from not important, to very important. These factors, which we validated with local experts before the circulation of the survey, were A) Soil and land characteristics; B) Crop characteristics; C) Water availability; D) Subsidies and grants; E) farm size; F) Passed down through the generations; G) Phytosanitary management.

Question 3.2: To what extent do the following factors influence the choice of conventional tillage?

Question 3.3: To what extent do the following factors influence the choice of reduced tillage?

Question 3.4: To what extent do the following factors influence the choice of No-tillage?

Question 3.5: Have you noticed any behavioural persistence or slow adoption of no-tillage practice? Answer Yes or No.

Question 3.6: If yes expand, if not, why do you think so? Text entry.

Question 3.7: In your opinion, are there opportunities to improve tillage practices through collaboration networks or co-creation plans? Answer Yes or No.

Question 3.8: If yes expand, if not, why do you think so? Text entry.

B.1.4 Irrigation practices

Question 4.1: Rank the following irrigation systems according to how commonly they are used in your area from 1 (most common) to 4 (least common). Answer selected from the following four responses: A) Surface irrigation; B) Localised irrigation; C) Sprinkler irrigation ; D) Rainfed lands.

To identify what factors most likely drive farmers' decision to adopt an irrigation system, we asked respondents to evaluate the contribution of 10 factors to the adoption of surface irrigation, Localised irrigation, and Sprinkler irrigation via a Likert scale with 3 points that range from not important, to very important. These factors were: A) Climate; B) Soil and land characteristics; C) Crop characteristics; D) Farm size; E) Labour availability; F) Availability of machinery and maintenance facilities; G) Capacity and readiness to invest; H) Profitability; I) Subsidies and grants; J) Water availability.

Question 4.2: To what extent do these factors lead farmers to adopt surface irrigation in your area?

Question 4.3: To what extent do these factors lead farmers to adopt localised irrigation in your area?

Question 4.4: To what extent do these factors lead farmers to adopt sprinkler irrigation in your area?

Question 4.5: In your area, how do farmers adapt to water shortages and other weather conditions? 1Text entry.

Question 4.6: In your opinion, are there opportunities to improve water management through collaboration networks or co-creation plans? Answer Yes or No.

Question 4.7: If yes expand, if not, why do you think so? Text entry.

B.1.5 Fertilizer management

Question 5.1: In your area, what type of fertilizer do farmers use the most? Answer selected from the following three responses: A) Organic fertilizers only; B) Predominance of organic fertilizers and limited use of chemical fertilizers; C) Equal use of both organic and chemical fertilizers; D) Predominance of chemical fertilizers and lower use of organic fertilizers.

To identify what factors most likely drive farmers' decision to adopt chemical or organic fertilizers, we asked respondents to evaluate the contribution of five factors with 3 points that range from not important, to very important. These factors were: A)

Profitability; B) Improved nutrient content; C) Environmentally friendly; D) High yield; E) Subsidies and grants.

Question 5.2: To what extent do the following factors influence the use of chemical fertilizers?

Question 5.3: To what extent do the following factors influence the use of organic fertilizers?

Question 5.4: How can you describe changes in the use of fertilizers? Answer selected from the following three responses: A) Predominance of organic fertilizers and absence or lower use of chemical fertilizers; B) Increase in the use of chemical fertilizers with a maintained use of organic fertilizers; C) Increase in the use of chemical fertilizers at the expense of organic fertilizers.

Question 5.5: To what extent do the following factors influence ***change*** *in fertilizer use?* To identify what factors, influence the change in fertilizer use, we asked respondents to evaluate the contribution of five factors with 3 points that range from not important, to very important. These factors were: A) Profitability; B) Improved nutrient content; C) Environmentally friendly; D) High yield; E) Subsidies and grants.

Question 5.6: In your opinion, are there opportunities to improve fertilizer practices through collaboration networks or co-creation plans? Answer Yes or No.

Question 5.7: If yes expand, if not, why do you think so? Text entry.

B.2 Climatic zones

Table B-1 Climatic zones in Morocco based on the *De Martonne* aridity index (1000 ha).

Region	Land Use	Climatic Zone					Total region area
		Arid	Humid and Subhumid	Hyperarid	Semi-arid	Grand Total	
Béni Mellal-Khénifra	Cropland		2775		4671	7446	
	Other		7415		12710	20125	27571
Drâa-Tafilalet	Cropland	446	60	553	610	1669	
	Other	24755	3320	42149	13461	83685	85353
Eddakhla-Oued Eddahab	Cropland			573		573	
	Other			129450		129450	130023
Fès-Meknès	Cropland	171	4744		6153	11068	
	Other	8681	4928		14626	28235	39303
Grand Casablanca-Settat	Cropland	2			8887	8889	
	Other	47			11106	11152	20041
Guelmim-Oued Noun	Cropland	53		129		182	
	Other	3236		41712		44948	45131
Laayoune-Sakia El Hamra	Cropland			895		895	
	Other			138871		138871	139765
Marrakech-Safi	Cropland	815	596		4848	6260	
	Other	8387	3277		21085	32749	39009
Oriental	Cropland	627	53	7	2482	3169	
	Other	27142	376	472	34470	62460	65628
Rabat-Salé-Kénitra	Cropland		3067		6132	9199	
	Other		2369		6006	8375	17574
Souss-Massa	Cropland	1537	192	64	862	2657	
	Other	18835	1571	16014	13558	49979	52635
Tanger-Tetouan-Al Hoceima	Cropland	9	7792		279	8080	
	Other	22	6227		1759	8008	16087
	Grand Total	94765	48762	370888	163706	678121	678121

To aggregate the responses per climatic zone, we considered only the cropland area of each region. Some of the administrative regions comprised a mixture of climatic zones. When the percentage of Subhumid to humid was between 30% and 90%, the region was attributed to the “Semi-arid and Subhumid to humid” classification. When the percentage exceeded 90%, it was attributed to the “Subhumid to humid” classification.

Table_ B-2 Agro-climatic zones of administrative regions of Morocco.

Agro-climatic zones	**Administrative regions**
Humid and Subhumid	Tanger-Tetouan-Al Hoceima
Semi-arid and subhumid to humid	Béni Mellal-Khénifra Fès-Meknès Rabat-Salé-Kénitra
Semi-arid	Grand Casablanca-Settat Marrakech-Safi Oriental
Arid to hyper arid	Drâa-Tafilalet Eddakhla-Oued Eddahab Souss-Massa Guelmim-Oued Noun Laayoune-Sakia El Hamra

Contextual questions

B.2.1 Crop Choices

Table_ B-3 Crop distribution across Morocco.

Crops	Total surface area (1000 ha)	Rank
Cereals	3795.46	1
Olive trees	1008.37	2
Forage crops	416.28	3
Horticultural crops	218.46	4
Legumes	210.04	5
Rosacea	206.08	6
Almond trees	165.82	7
Citruses	122.47	8
Industrial crops	64.87	9
Date palm trees	58.12	10
Oilseed crop	54.49	11
Vine	46.00	12

Table_ B-4 Estimated crop areas in 2016 for each climatic zone in Morocco.

Crops	Surface area (1000 ha)			
	Subhumid to humid	Semi-arid and subhumid to humid	Semi-arid	Arid to hyperarid
Cereals	382.59	1630.25	1607.66	174.96
Legumes	36.57	151.32	21.25	0.91
Oilseed crop	6.95	47.54	0.00	0.00
Industrial crops	30.00	28.48	4.48	1.91
Forage crop	51.79	217.45	133.85	13.20
Horticultural crops	22.43	87.72	86.44	21.86
Citruses	1.94	44.52	36.03	39.98
Almond tree	29.41	53.64	42.04	40.72
Olive tree	157.39	479.64	337.02	34.32
Date palm trees	0.00	0.00	1.74	56.38
Vine	1.71	16.91	26.83	0.55
Rosacea	28.01	107.68	39.63	30.76

B.2.2 Tillage

Table_ B-5 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by conventional tillage.

Rank	Arid-hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	8	4	15	26	53
2	0	0	1	2	3
3	2	0	0	2	4

Table_ B-6 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by reduced tillage.

Rank	Arid-hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	0	0	0	3	3
2	8	4	12	17	41
3	2	0	4	10	16

Table_ B-7 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by no-tillage.

Rank	Arid-hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	2	0	1	3	6
2	2	0	3	10	15
3	6	4	12	17	39

Table_ B-8 Friedman's test – tillage.

Data variate	Rank
Blocks	Participant_ID
Treatments	Tillage systems
Number of blocks	87
Number of treatments	3
Friedman's statistic	94.36
Adjusted for ties	96.58
Degrees of freedom	2
P-value using chi-square approximation (2 d.f.)	0.000

Irrigation

Table_ B-9 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by the rank of surface irrigation.

Rank	Arid-Hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	1	0	3	4	8
2	3	2	3	9	17
3	7	0	3	3	13
4	1	1	3	2	7

Table_ B-10 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by the rank of localized irrigation.

Rank	Arid-Hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	8	2	7	6	23
2	1	0	2	2	5
3	2	1	2	5	10
4	1	0	1	5	7

Table_ B-11 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by the rank of sprinkler irrigation.

Rank	Arid-Hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	1	0	0	0	1
2	6	1	2	3	12
3	0	1	5	7	13
4	5	1	5	8	19

Table_ B-12 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by the rank of rain-fed lands.

Rank	Arid-Hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
1	3	1	3	8	15
2	1	1	4	4	10
3	4	1	3	4	12
4	4	0	2	2	8

Table_ B-13 Friedman's test – irrigation.

Data variate	Rank
Blocks	Respondents _ID
Treatments	Irrigation systems
Number of blocks	46
Number of treatments	4
Friedman's statistic	17.71
Adjusted for ties	17.75
Degrees of freedom	3
P-value using chi-square approximation (3 d.f.)	p<0.0001

B.2.3 Fertilizer management

Table_ B-14 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by fertilizer type.

Fertilizers	Arid-Hyperarid	Subhumid to humid	Semi-arid	Semi-arid / Subhumid to humid	Total
Equal use of both organic and chemical fertilizers	1	1	1	2	5
Organic fertilizers only	0	0	1	1	2
The predominance of chemical fertilizers and lower use of organic fertilizers	5	3	8	11	27
The predominance of organic fertilizers and limited use of chemical fertilizers	4	1	2	2	9

B.3 Factors affecting management choices

B.3.1 Crop Choices

Table_ B-15 The contingency table showing how many individuals selected a given general factor influencing crop selection. The table is presented according to factors and pooled by the degree of importance.

Influencing factors	Environmental factors	Economic factors	Social factors	Crop characteristics	Farm size and facilities
Not important	30	69	52	29	46
Moderately important	87	177	91	154	147
Very important	184	205	83	189	102
	Expected values - came out of GenStat				
Not important	41.35	61.96	31.05	51.11	40.53
Moderately important	120.03	179.85	90.13	148.35	117.64
Very important	139.61	209.19	104.83	172.54	136.83

Table_ B-16 The contingency table showing how many individuals selected a given response to Question 2.1. The table is presented according to factors and pooled by the degree of importance.

	Environmental factors			
	Climate	**Soil and land characteristics**	**Water availability**	**Previous crop**
Not important	0	3	3	24
Moderately important	13	29	9	36
Very important	63	43	62	16
	Expected values - came out of GenStat			
Not important	7.58	7.48	7.38	7.58
Moderately important	21.97	21.68	21.39	21.97
Very important	46.46	45.85	45.24	46.46

Table_ B-17 The contingency table showing how many individuals selected a given response to Question 2.2. The table is presented according to factors and pooled by the degree of importance.

	Economic factors					
	Subsidies and grants	**Labour availability**	**Capacity and readiness to invest**	**Contract with industries**	**Crop insurance**	**Profitability**
Not important	5	4	10	20	29	1
Moderately important	25	28	49	29	29	17
Very important	45	43	17	25	18	57
	Expected values - came out of GenStat					
Not important	11.47	11.47	11.63	11.32	11.63	11.47
Moderately important	29.43	29.43	29.83	29.04	29.83	29.43
Very important	34.09	34.09	34.55	33.64	34.55	34.09

Table_ B-18 The contingency table showing how many individuals selected a given response to Question 2.3. The table is presented according to factors and pooled by the degree of importance.

	Social factors		
	Prior experience with the crop	**Passed down through the generations**	**Education**
Not important	5	12	35
Moderately important	25	39	27
Very important	46	24	13
	Expected values - came out of GenStat		
Not important	17.49	17.26	17.26
Moderately important	30.6	30.2	30.2
Very important	27.91	27.54	27.54

Table_ B-19 The contingency table showing how many individuals selected a given response to Question 2.4. The table is presented according to factors and pooled by the degree of importance.

	Crop characteristics				
	Resistance to pests and diseases	**Drought resistance**	**Maturity dates**	**High yield**	**Length of the growing season**
Not important	9	7	9	0	4
Moderately important	29	30	37	17	41
Very important	37	36	30	56	30
	Expected values - came out of GenStat				
Not important	5.85	5.69	5.92	5.69	5.85
Moderately important	31.05	30.22	31.46	30.22	31.05
Very important	38.1	37.09	38.61	37.09	38.1

Table_ B-20 The contingency table showing how many individuals selected a given response to Question 2.5. The table is presented according to factors and pooled by the degree of importance.

	Farm size and facilities			
	Farming system	**Availability of machinery and maintenance facilities**	**Storage facility or accessibility**	**Technology**
Not important	6	9	13	18
Moderately important	34	36	40	37
Very important	32	30	20	20
	Expected values - came out of GenStat			
Not important	11.23	11.69	11.38	11.69
Moderately important	35.88	37.37	36.38	37.37
Very important	24.89	25.93	25.24	25.93

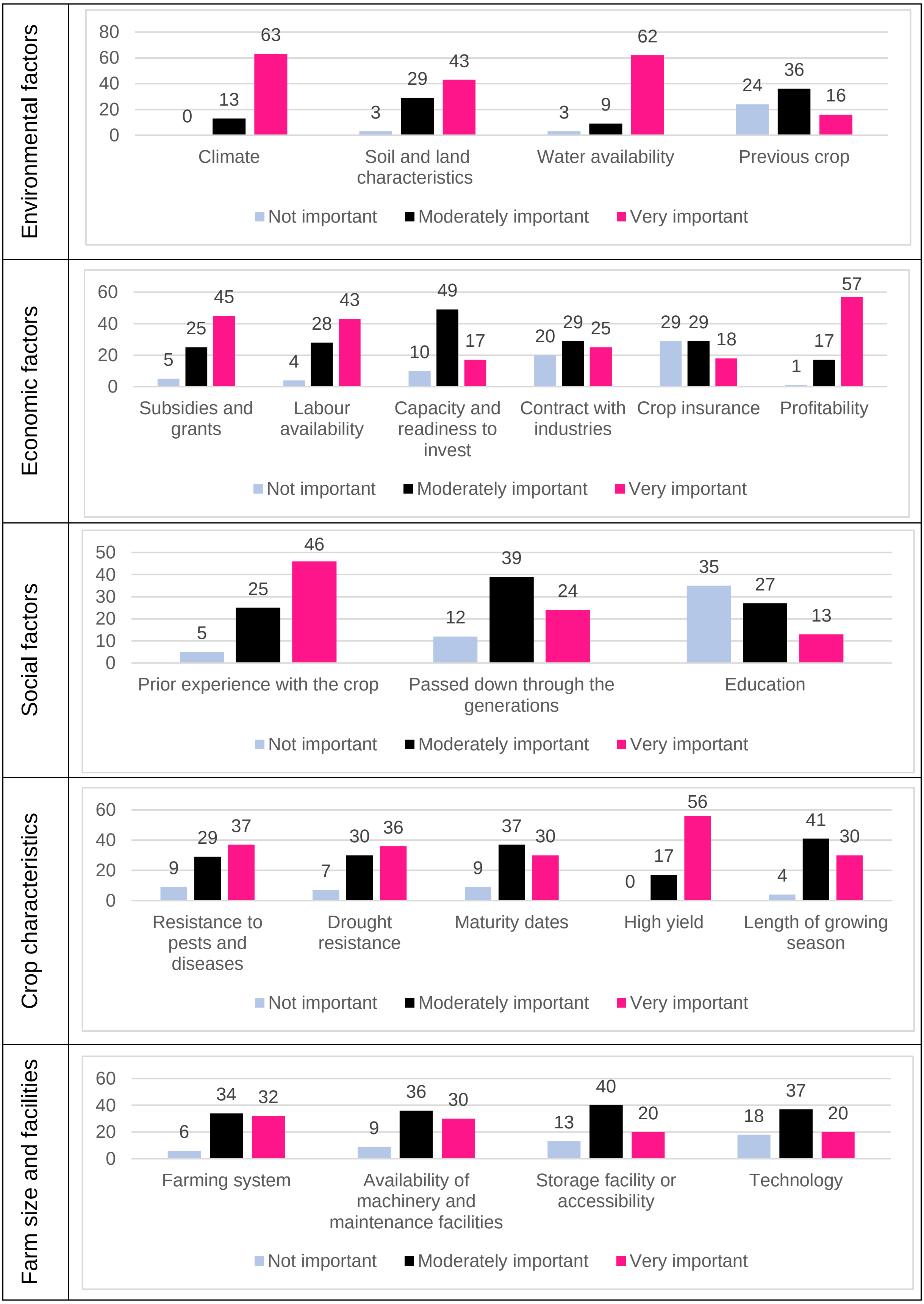


Figure_ B-1 Number of responses recorded per sub-factor influencing crop choices.

B.3.2 Tillage

Table_ B-21 Accumulated analysis of deviance of tillage systems.

Change	**d.f.**	**Deviance**	**Mean deviance**	**Deviance ratio**	**Approx χ^2 pr**
Tillage	2	0.6523	0.3262	0.33	0.722
Factor	6	0.0596	0.0099	0.01	1.000
Tillage.Factor	12	0.1393	0.0116	0.01	1.000
Importance	2	106.9309	53.4655	53.47	<.001
Tillage.Importance	4	12.8177	3.2044	3.20	0.012
Factor.Importance	12	97.4109	8.1176	8.12	<.001
Residual	24	21.6974	0.9041		
Total	62	239.7080	3.8663		

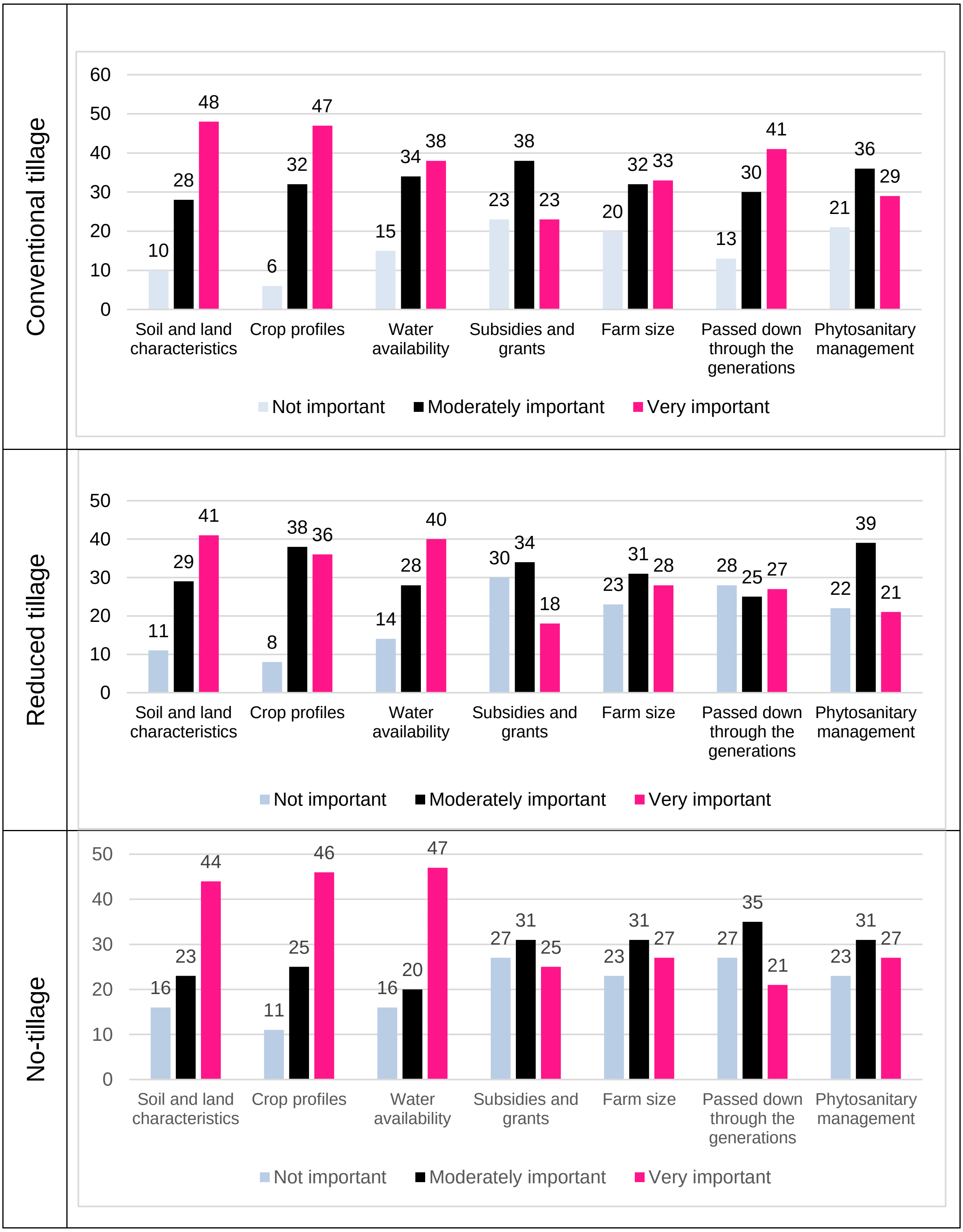


Figure_ B-2 Number of responses recorded per factors influencing the choice of tillage systems.

Table_ B-22 The contingency table showing how many individuals selected a given response to Question 3.2. The table is presented according to factors and pooled by the degree of importance. The Influencing factors are A) soil and land characteristics; B) Crop characteristics; C) water availability; D) Subsidies and grants; E) farm size; F) passed down through the generations; G) phytosanitary management.

	Conventional tillage						
	Soil and land characteristics	**Crop characteristics**	**Water availability**	**Subsidies and grants**	**farm size**	**Passed down through the generations**	**Phytosanitary management**
Not important	10	6	15	23	20	13	21
Moderately important	28	32	34	38	32	30	36
Very important	48	47	38	23	33	41	29
	Expected values - came out of GenStat						
Not important	15.56	15.38	15.74	15.2	15.38	15.2	15.56
Moderately important	33.13	32.75	33.52	32.36	32.75	32.36	33.13
Very important	37.31	36.88	37.74	36.44	36.88	36.44	37.31

Table_ B-23 The contingency table showing how many individuals selected a given response to Question 3.3. The table is presented according to factors and pooled by the degree of importance. The Influencing factors are A) soil and land characteristics; B) Crop characteristics; C) water availability; D) Subsidies and grants; E) farm size; F) passed down through the generations; G) phytosanitary management.

	Reduced tillage						
	Soil and land characteristics	**Crop profile**	**Water availability**	**Subsidies and grants**	**farm size**	**Passed down through the generations**	**Phytosanitary management**
Not important	11	8	14	30	23	28	22
Moderately important	29	38	28	34	31	25	39
Very important	41	36	40	18	28	27	21
	Expected values - came out of GenStat						
Not important	19.29	19.53	19.53	19.53	19.53	19.05	19.53
Moderately important	31.78	32.17	32.17	32.17	32.17	31.38	32.17
Very important	29.93	30.3	30.3	30.3	30.3	29.56	30.3

Table_ B-24 The contingency table showing how many individuals selected a given response to Question 3.4. The table is presented according to factors and pooled by the degree of importance. The Influencing factors are A) soil and land characteristics; B) Crop characteristics; C) water availability; D) Subsidies and grants; E) farm size; F) passed down through the generations; G) phytosanitary management.

	No-tillage						
	Soil and land characteristics	**Crop profile**	**Water availability**	**Subsidies and grants**	**farm size**	**Passed down through the generations**	**Phytosanitary management**
Not important	16	11	16	27	23	27	23
Moderately important	23	25	20	31	31	35	31
Very important	44	46	47	25	27	21	27
	Expected values - came out of GenStat						
Not important	20.61	20.36	20.61	20.61	20.11	20.61	20.11
Moderately important	28.24	27.9	28.24	28.24	27.56	28.24	27.56
Very important	34.15	33.74	34.15	34.15	33.33	34.15	33.33

B.3.3 Irrigation

Table_ B-25 Accumulated analysis of deviance across all irrigation systems.

Change	**d.f.**	**Deviance**	**Mean deviance**	**Deviance ratio**	**Approx. chi pr**
Irrigation_systems	2	5.344	2.672	2.67	0.069
Factors	7	1.203	0.172	0.17	0.991
Irrigation_systems.Factors	14	0.129	0.009	0.01	1
Importance	2	117.09	58.545	58.55	<.001
Irrigation_systems.Importance	4	49.317	12.329	12.33	<.001
Factors.Importance	14	97.532	6.967	6.97	<.001
Residual	28	41.359	1.477		
Total	71	311.975	4.394		

Table_ B-26 Accumulated analysis of deviance of localized and sprinkler irrigation.

Change	**d.f.**	**Deviance**	**Mean deviance**	**Deviance ratio**	**Approx chi pr**
Irrigation_systems	1	0.33	0.33	0.33	0.566
Factors	1	0.021	0.021	0.02	0.886
Irrigation_systems.Factors	1	0.000	0.000	0.00	0.995
Importance	2	55.258	27.629	27.63	<.001
Irrigation_systems.Importance	2	34.653	17.327	17.33	<.001
Factors.Importance	2	8.809	4.404	4.4	0.012
Residual	2	5.04	2.52		
Total	11	104.111	9.465		

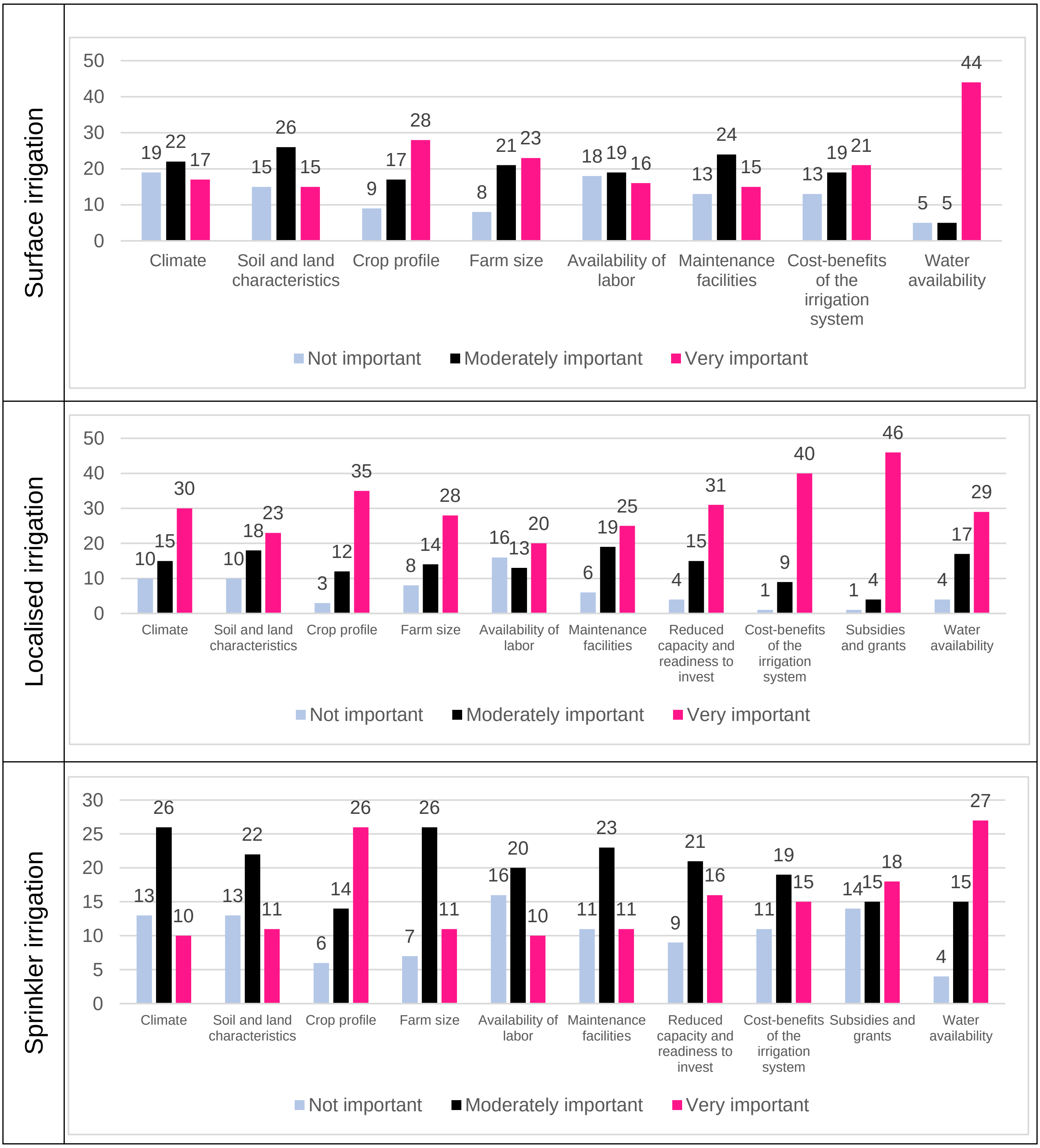


Figure_ B-3 Number of responses recorded per factors influencing the choice of irrigation systems.

Table_ B-27 The contingency table showing how many individuals selected a given response to Question 4.2. The table is presented according to factors and pooled by the degree of importance.

	Surface irrigation							
	Climate	**Soil and land characteristics**	**Crop characteristics**	**Farm size**	**Labour availability**	**Availability of machinery and maintenance facilities**	**Profitability**	**Water availability**
Not important	19	15	9	8	18	13	13	5
Moderately important	22	26	17	21	19	24	19	5
Very important	17	15	28	23	16	15	21	44
	Expected values - came out of GenStat							
Not important	13.43	12.96	12.5	12	12.27	12.04	12.27	12.5
Moderately important	20.54	19.83	19.13	18.4	18.77	18.42	18.77	19.13
Very important	24.03	23.2	22.37	21.6	21.96	21.55	21.96	22.38

Table_ B-28 The contingency table showing how many individuals selected a given response to Question 4.3. The table is presented according to factors and pooled by the degree of importance.

	Localized irrigation									
	Climate	**Soil and land characteristics**	**Crop characteristics**	**Farm size**	**Labour availability**	**Availability of machinery and maintenance facilities**	**Capacity and readiness to invest**	**Profitability**	**Subsidies and grants**	**Water availability**
Not important	10	10	3	8	16	6	4	1	1	4
Moderately important	15	18	12	14	13	19	15	9	4	17
Very important	30	23	35	28	20	25	31	40	46	29
	Expected values - came out of GenStat									
Not important	6.85	6.35	6.23	6.23	6.1	6.23	6.23	6.23	6.35	6.23
Moderately important	14.78	13.71	13.44	13.4	13.17	13.44	13.44	13.44	13.71	13.44
Very important	33.37	30.94	30.34	30.3	29.73	30.34	30.34	30.34	30.94	30.34

Table_ B-29 The contingency table showing how many individuals selected a given response to Question 4.4. The table is presented according to factors and pooled by the degree of importance.

	Sprinkler irrigation									
	Climate	**Soil and land characteristics**	**Crop characteristics**	**Farm size**	**Labour availability**	**Availability of machinery and maintenance facilities**	**Capacity and readiness to invest**	**Profitability**	**Subsidies and grants**	**Water availability**
Not important	13	13	6	7	16	11	9	11	14	4
Moderately important	26	22	14	26	20	23	21	19	15	15
Very important	10	11	26	11	10	11	16	15	18	27
	Expected values - came out of GenStat									
Not important	11.08	10.4	10.4	9.95	10.4	10.17	10.4	10.17	10.63	10.4
Moderately important	21.41	20.1	20.1	19.23	20.1	19.66	20.1	19.66	20.54	20.1
Very important	16.51	15.5	15.5	14.83	15.5	15.16	15.5	15.16	15.84	15.5

B.3.4 Fertilizer management

Table_ B-30 Accumulated analysis of deviance of fertilizers.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx chi pr
Fertilizers	1	0.009	0.009	0.01	0.924
Factors	4	0.054	0.014	0.01	1
Fertilizers.Factors	4	0.036	0.009	0.01	1
Importance	2	20.1	10.05	10.05	<.001
Fertilizers.Importance	2	4.844	2.422	2.42	0.089
Factors.Importance	8	105.501	13.188	13.19	<.001
Residual	8	53.957	6.745		
Total	29	184.502	6.362		

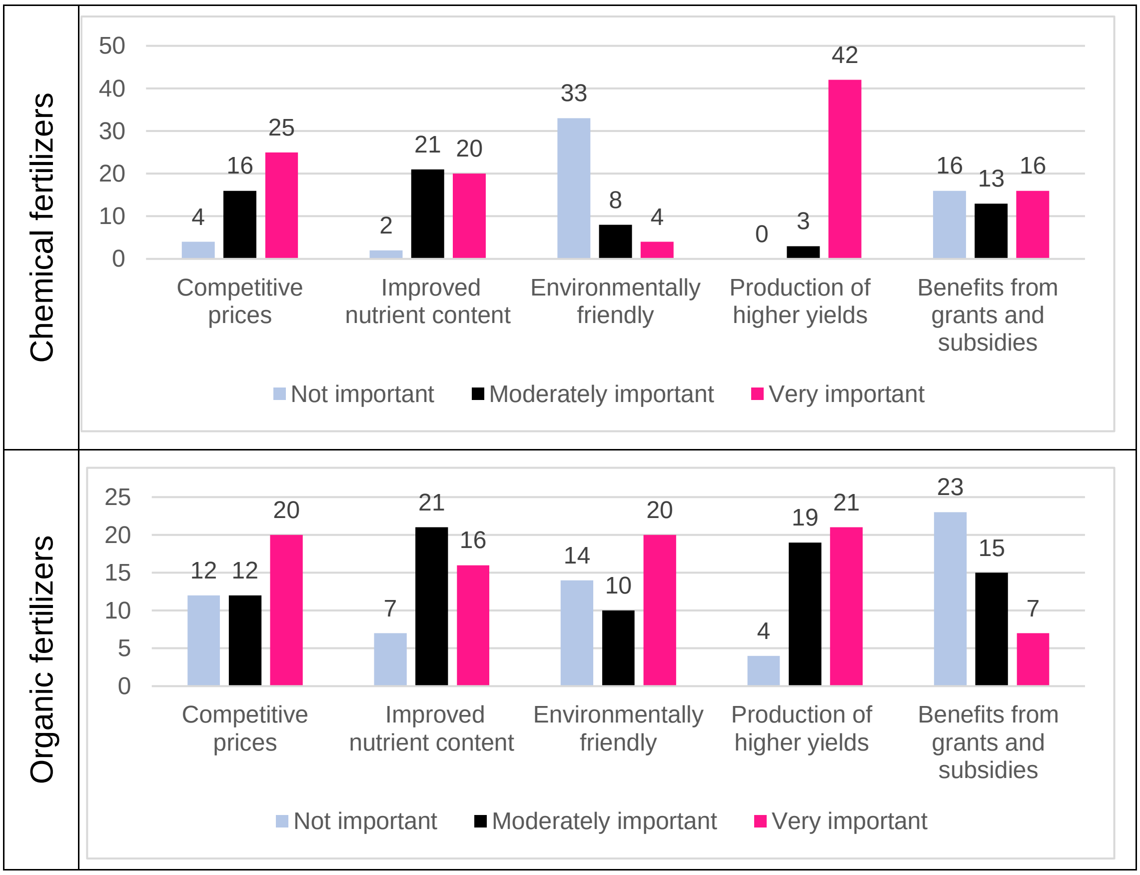


Figure_ B-4 Number of responses recorded per factors influencing the choice of fertilizers.

Table_ B-31 The contingency table showing how many individuals selected a given response to Question 5.2. The table is presented according to factors and pooled by the degree of importance.

	Chemical fertilizers				
	Profitability	**Improved nutrient content**	**Environmentally friendly**	**High yield**	**Grants and subsidies**
Not important	4	2	33	0	16
Moderately important	16	21	8	3	13
Very important	25	20	4	42	16
	Expected values - came out of GenStat				
Not important	11.1	10.61	11.1	11.1	11.1
Moderately important	12.31	11.76	12.31	12.31	12.31
Very important	21.59	20.63	21.59	21.59	21.59

Table_ B-32 The contingency table showing how many individuals selected a given response to Question 5.3. The table is presented according to factors and pooled by the degree of importance.

	Organic fertilizers				
	Profitability	**Improved nutrient content**	**Environmentally friendly**	**High yield**	**Grants and subsidies**
Not important	12	7	14	4	23
Moderately important	12	21	10	19	15
Very important	20	16	20	21	7
	Expected values - came out of GenStat				
Not important	11.95	11.95	11.95	11.95	12.22
Moderately important	15.33	15.33	15.33	15.33	15.68
Very important	16.72	16.72	16.72	16.72	17.1

Behavioural persistence, change or adaptation

B.3.5 Crop Choices

Table_ B-33 The contingency table showing how many individuals selected a given response according to climatic zones. The table is presented according to climatic zones and pooled by the willingness/unwillingness to adopt agroforestry.

Agroforestry	**Arid to hyperarid**	**Subhumid to humid**	**Semi-arid**	**Semi-arid / Subhumid to humid**
Willingness	7	2	17	18
Unwillingness	8	3	5	7

B.3.6 Fertilizer management

Table_ B-34 The contingency table showing how many individuals selected a given response to Question 5.4. The table is presented according to factors and pooled by the degree of importance.

	Change in the use of fertilizers				
	Profitability	**Improved nutrient content**	**Environmentally friendly**	**High yield**	**Grants and subsidies**
Not important	4	2	14	1	11
Moderately important	6	11	14	2	7
Very important	29	25	11	37	21
	Expected values - came out of GenStat				
Not important	6.4	6.24	6.4	6.56	6.4
Moderately important	8	7.79	8	8.21	8
Very important	24.6	23.97	24.6	25.23	24.6

Appendix C Supplementary material for Chapter Three

Table_ C-1 Latent variables and observed statements for drip irrigation adoption.

Latent variables	Observed statements
Behaviour	I am planning to adopt drip irrigation
Intention	I am willing to apply for a drip irrigation subsidy I am willing to dig a well
Subjective norms	I am aware that the government is promoting the adoption of drip irrigation My neighbours are satisfied with drip irrigation
Attitude	I am satisfied with drip irrigation efficiency I am satisfied with groundwater salinity I am satisfied with the groundwater supply
Perceived Behavioural Control	My type of tenure facilitates the adoption of drip irrigation My farm size facilitates the adoption of drip irrigation

Appendix D Supplementary material for Chapter Four

D.1 Simulated areas

To generate the farm areas, we use the farm areas reported by the farmers in our survey (El Fartassi et al., 2024). We use the MATLAB Statistics toolbox (The Mathworks, 2022) to fit a lognormal distribution to the survey data (mu = 1.88 and sigma = 1.20). The distributions considered were Weibull, Lognormal, Gamma, and Log-logistic. We visually examined the fit by using a histogram and a quantile-quantile plot and used the chi-square goodness-of-fit test to determine the best fit. The p-value of the Lognormal distribution was higher than the log-logistic and Weibull distributions, making it the best fit for the sample.

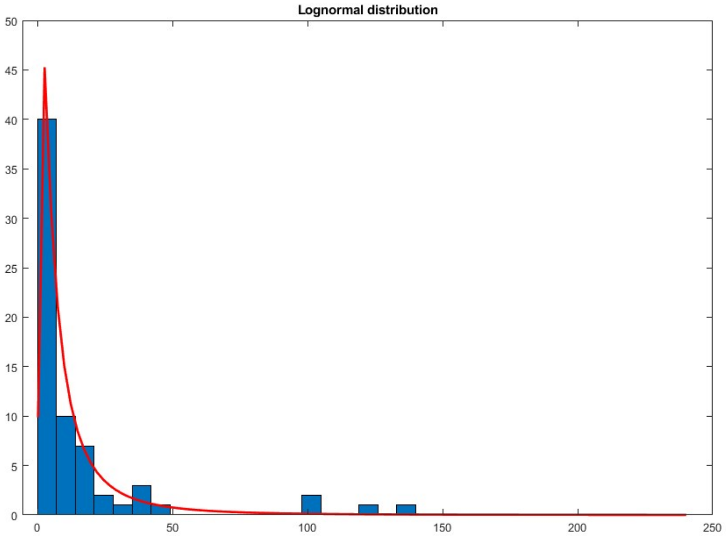


Figure_ D-1 Histogram of farm area (ha) with a lognormal distribution fit.

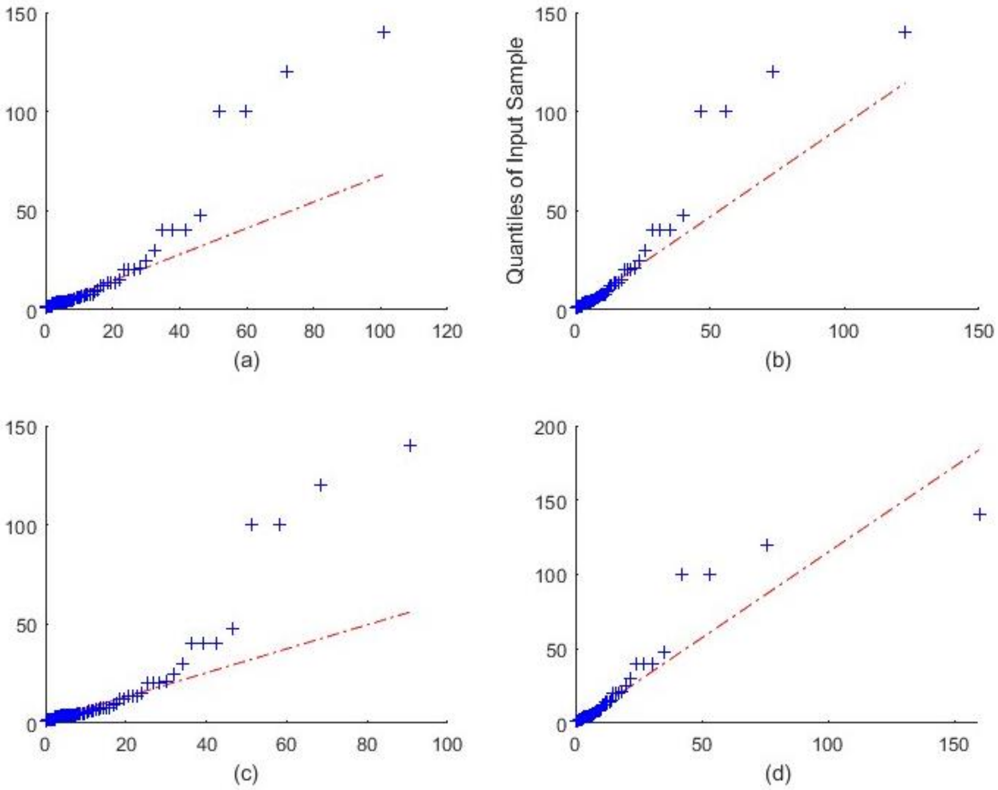


Figure_ D-2 Quantile-quantile plot of the input sample quantiles of y versus theoretical quantiles from a) Weibull distribution b) Lognormal c) Gamma distribution d) Log-logistic distribution.

Table_ D-1 Comparison of fit distributions for the simulated areas.

	h	*p*
Lognormal	**0**	**0.2434**
Loglogistic	0	0.2369
Weibull	0	0.0715
Gamma	1	0.0047

D.2 Simulating initial groundwater attitude values

To generate initial conditions for attitude values regarding groundwater appreciation, we sampled from three parameterised beta distributions to capture attitudinal divergence across irrigation categories. For our initial conditions, we assume that those who have already invested in groundwater are more likely to have a positive attitude towards it than those who use dam water alone.

For the groundwater-only category, we defined a positively skewed beta distribution with to reflect greater hypothesized appreciation (α = 8 and β = 7, giving 62% with an attitude value greater than 0.5).

For mixed source irrigation, we used positive skew beta distribution with a smaller mode (α = 5.5 and β = 4.3 giving 54% with an attitude value greater than 0.5).

For dam-only farmers, we defined a negatively skewed beta distribution (α = 6.4 and β = 8.6,) giving only 23% above 0.5 to reflect a lower initial positive attitude to groundwater.

D.3 Simulating initial affordability values

The affordability values are based on the economies of scale principle, which suggests that as the scale of production increases, the cost per unit of output decreases (Michael, 2009). We assume that a farmer operating at a larger scale finds it more affordable to invest in new wells due to cost efficiencies. In contrast, smaller-scale farmers often face more constraints in their decision-making processes due to tighter operational margins and limited access to capital, which can restrict their ability to make substantial investments. Given these differences in affordability based on farm size and access to resources, we model the distinct investment capabilities of various farmer typologies using beta distributions. To generate simulated affordability data for different farmer typologies, we configure separate beta distributions by setting distinct shape parameters, α and β, for each group.

The choice of paired parameters α and β for each farmer type were deliberately chosen to sample data that conform to these general profitability assumptions across scales.

For generating simulated affordability data for small-scale farmers, we defined a beta distribution with α = 8.4 and β = 7. By setting α higher than β, this skews the distribution toward higher affordability values, with increased density above a hypothetical profitability threshold of 0.5. From this distribution, we sampled 102 data points. The number of samples is set higher to better represent the larger population size of this farmer typology.

For medium-scale farmers, we defined a beta distribution with parameters $\alpha = 9$ and $\beta = 6$. We sampled 108 data points from this skewed distribution which represents a typical population quantity for the medium-scale farmer typology.

For large-scale farmers, we sharply skewed affordability figures by choosing more disparate beta distribution parameters at $\alpha = 10$ and $\beta = 5$. This yields a distribution concentrated heavily towards affordability substantially exceeding the hypothetical threshold at 0.5. From this right-skewed shape, we took a sample of 38 affordability data points. The choice of distribution plus modest sampling quantity creates modelled data consistent with high-resourced, large-scale farming entities and their underlying economic capabilities.

These parameters and the resulting simulated proportions of affordability greater than 0.5 were carefully selected to mirror the economic realities of each farmer group.

D.4 Simulating initial tenancy values

Of the farmers we surveyed, 90% were owners and 10% were renters. We simulated 248 farmers following this characterization. We note that this characterization is based on our survey sample and may not necessarily represent the entire study area. A farmer's owner or tenant status represents the legal and contractual rights underpinning farm operations and so can significantly influence their *PBC* when it comes to investing in new infrastructure. Land ownership often provides farmers with greater PBC, as they have more autonomy in decision-making and can make long-term investments. Owned land can also serve as collateral for loans, increasing access to capital for investments in wells (Lawry et al., 2017). In contrast, tenant farmers may perceive less control over their ability to invest in new wells due to the need to negotiate with landlords and the potential for shorter lease terms, which can create uncertainty and discourage long-term investments.

To initialise values PBC for different land tenure categories, we configured separate beta distributions by setting distinct shape parameters, α and β, for owners and renters using the ***betarnd*** MATLAB function.

The choice of α and β values is not empirically based but rather selected intentionally to reflect assumptions about PBC levels exceeding a hypothetical threshold of 0.5 for each tenure category.

Specifically, a higher α skews the distribution towards more frequent PBC figures above 0.5, while a lower β also shifts density to the right of the threshold. The paired parameters for each tenure type were deliberately chosen to generate data conforming to general assumptions about PBC across owner and renter categories.

For simulating data for owners, we defined a beta distribution with parameters $\alpha = 9.1$ and $\beta = 5.9$. Setting a higher α than β skews the distribution toward higher perceived control values, with increased density above the 0.5 threshold. We sampled 223 data points from this right-skewed distribution. For renters, we defined a beta distribution with symmetrical parameters $\alpha = 7.5$ and $\beta = 7.5$. From this distribution, we sampled 25 data points, set lower to reflect the smaller share of agricultural land operated by renters. The parameters and resulting simulated proportions of perceived control exceeding 0.5 for each category were carefully chosen to reflect theorized differences in land tenure.

The legal and contractual rights associated with land ownership and tenancy can also interact with other factors, such as the economies of scale and access to capital, to shape a farmer's overall affordability and decision-making when investing in new wells. Following a similar approach of using beta distributions, we generated simulated affordability data for different farmer typologies as below.

D.5 Simulated salinity

D.5.1 Derivation of soil salinity

If W is constant, then

$$S(t) = \varphi - [\varphi - S(t-1)]W(EC_w)$$

Can be written

$$S(t) = \varphi - [\varphi - S(0)]W^t$$

After three years $S(t) = 0.9E_w$

$$0.9E_w = \varphi - [\varphi - S(0)]W^3$$

Rearranging

$$\frac{\varphi - 0.9E_w}{\varphi - S(0)} = W^3$$

Therefore

$$W = \left(\frac{\varphi - 0.9E_w}{\varphi - S(0)}\right)^{\frac{1}{3}}$$

Table_ D-2 shows the parameter values used to fit a logistic irrigation response curve for a sowing date corresponding to the 24th of December with total irrigation as a dependent variable.

Table_ D-2 Irrigation parameters.

Parameters	**Value**
B	0.01041
M	147.3
C	4.395
A	-0.5031

D.5.2 Salinity distribution

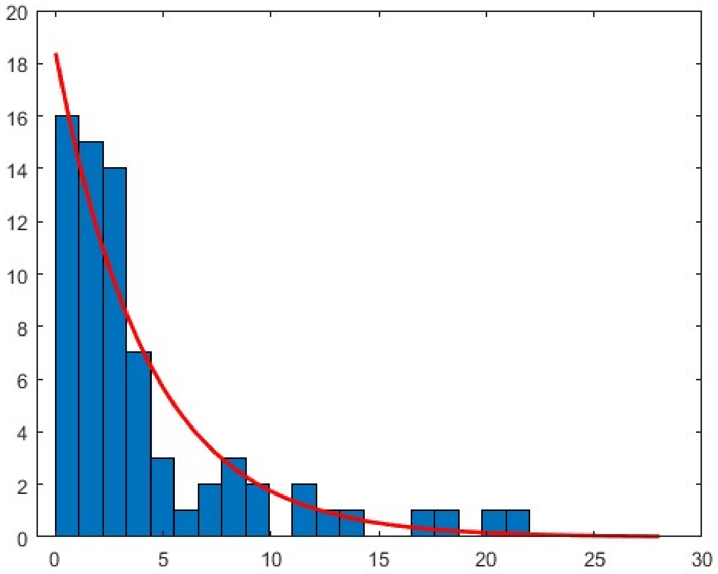


Figure_ D-4 Histogram of salinity (dS/m) with an exponential distribution fit.

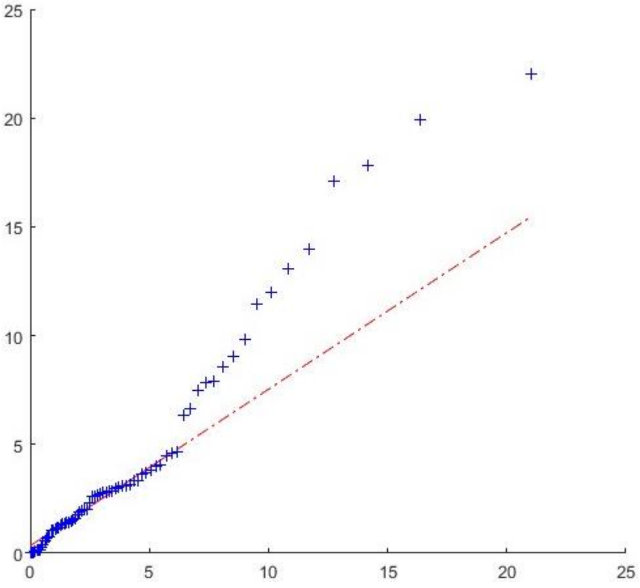


Figure_ D-3 Quantile-quantile plot of the input sample quantiles dS/m of y versus theoretical quantiles dS/m from an exponential distribution.

The results show that the Kernel distribution is too sensitive and overfitting. The p-value of the exponential distribution is higher than the others, making it the best fit for the sample (Table_ D-3).

Table_ D-3 Comparison of fit distributions for salinity.

	h	**p**
Exponential	**0**	**0.1651**
Weibull	0	0.0869
Gamma	0	0.0805
Loglogistic	0	0.0526
Lognormal	1	0.0095

Table_ D-4 Temporal variations in irrigation allocation and water needs in R3.

Agricultural season	**Water allocation**	**Water need**	**Proportions**	**Caped proportions**
87-88	197.36	310	0.64	0.64
88-89	395.32	310	1.28	1.00
89-90	340.87	310	1.10	1.00
90-91	224.43	310	0.72	0.72
91-92	303.61	310	0.98	0.98
92-93	188.12	310	0.61	0.61
93-94	149.62	310	0.48	0.48
94-95	152.59	310	0.49	0.49
95-96	110.52	310	0.36	0.36
96-97	145.56	310	0.47	0.47
97-98	173.43	310	0.56	0.56
98-99	167.37	310	0.54	0.54
99-00	162.68	310	0.52	0.52
00-01	72.62	310	0.23	0.23
2001-2002	48.39	310	0.16	0.16
2002-2003	70.25	310	0.23	0.23
2003-2004	93.48	310	0.30	0.30
2004-2005	138.99	310	0.45	0.45
2005-2006	129.23	310	0.42	0.42
2006-2007	128.53	310	0.41	0.41
2007-2008	96.03	310	0.31	0.31
2008-2009	90.45	310	0.29	0.29
2009-2010	126.59	310	0.41	0.41
2010-2011	160.18	310	0.52	0.52
2011-2012	146.79	310	0.47	0.47
2012-2013	138.03	310	0.45	0.45
2013-2014	114.45	310	0.37	0.37
2014-2015	108.81	310	0.35	0.35
2015-2016	160.08	310	0.52	0.52
2016-2017	141.49	310	0.46	0.46
2017-2018	78.46	310	0.25	0.25
2018-2019	141.79	310	0.46	0.46
2019-2020	43.70	310	0.14	0.14