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Climate resilience and the human-water dynamics. The case of tomato production in Morocco

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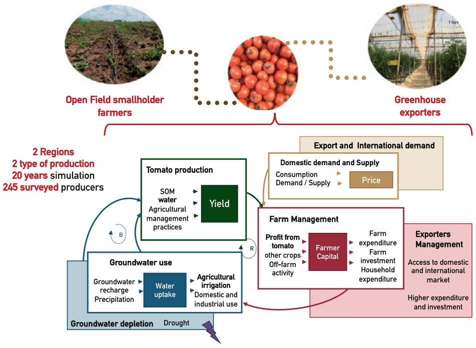
HIGHLIGHTS

- Repetitive droughts are accelerating the process of groundwater depletion in Morocco.
- Water scarcity will severely impact farmer's livelihood over a longer time period.
- Water resource conservation are necessary to enhance a sustainable and inclusive resilience.
- The interconnections within the socio-ecological systems must be taken into account when designing policies.

GRAPHICAL ABSTRACT



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ABSTRACT

In Morocco, droughts are an increasing threat affecting water availability, agricultural production and producers' livelihoods. Moreover, water demand for irrigation has led to overexploitation of the groundwater table causing significant natural resource management challenges. The combination of groundwater changes and increasing drought risk raises concerns about the ability of agricultural producers to be resilient against drought. In this study, we describe the interactions of environmental and socioeconomic processes which influence farmers' livelihoods involved in tomato production in Morocco. Building on system dynamics modelling tools, we aim to improve the understanding of the long-term dynamic behavior of water management and to explore plausible policy scenarios necessary for sustainable and resilient water resource management and agricultural development. Our results show that tomato production is not yet severely impacted by droughts. However, droughts are accelerating the process of groundwater depletion, impacting farmers' livelihoods, by decreasing crop productivity and reducing farmer's revenue over a longer time period, especially since tomatoes are a high-value crop. Therefore, integrated and effective policies are presented as a set of measures for a systemic enhancement of resilience. We conclude that a more radical approach toward water resource conservation and upholding the most vulnerable producers has to be adopted in order to enhance a sustainable and inclusive resilience of the tomato production in Morocco.

1. Introduction

Changes in temperature and rainfall are threatening crop yields, crop producers and, in general, the whole agricultural sector (Smith et al.,

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2007). This raises concerns about the ability of food systems to be resilient in face of further weather extremes (Shenggen et al., 2014). Disturbances, such as droughts, have a direct influence on socio-ecological systems, such as agroecosystems inherently are, at multiple spatial (i.e. from field to farm to region) (Redman, 2014) and temporal scales (i.e. from days to seasons to decades) (Meacham, 2016). For example, a combination of rising temperatures and abnormally low precipitation patterns results in higher water demand for agricultural irrigation (Johannsen et al., 2016; Karmaoui, 2015), which is the case especially in North-Africa and more particularly in a country like Morocco (Messouli et al., 2009; Rochdane et al., 2014). Hence, under increasing risk of drought, water resources management needs to balance between conserving water resources and maintaining an adequate supply for agricultural use (Iglesias et al., 2007). Thus, the impacts of a drought on an agricultural system are usually a combination of the weather shock itself and the resilience of different parts of this system (Rey et al., 2017). Within such context, there is a need to investigate the current and potential future impacts of droughts on farmers to ultimately address how farmers' resilience could be challenged in the long-term. Building on a complementary study addressing water resources depletion in Morocco (Benabderrazik et al., 2021), we aim to further investigate the effects of droughts on farmer's resilience.

Resilience has widely been used as a key concept to understand and address the capacity of a system to deal with disturbances and shocks (Adger, 2000; Folke, 2006; Holling, 2001). In socio-ecological systems, resilience has been extensively conceptualized by focusing on non-linear dynamics, thresholds and uncertainty (Adger, 2000; Carpenter et al., 2014; Folke, 2006; Holling, 2001; Walker et al., 2004). In food systems, resilience thinking led to an approach based on integration of ecological and social aspects, which aims to identify measures to limit the impact of a disturbance on nature and people (Cabell and Oelofse, 2012; Darnhofer et al., 2010; Jacobi et al., 2015). More recent studies discuss frameworks to enhance the resilience in food systems at a regional or a global level (Bullock et al., 2017; Tendall et al., 2015b). Among a substantial amount of existing resilience frameworks, individual farm system resilience has been conceptualized by several studies (Darnhofer et al., 2010; Jacobi et al., 2015; Milestad and Darnhofer, 2003; Schuster and Colby, 2013), but the complexity of farming systems and their dynamics over time and space remains challenging to provide specific guidance on how farmers should deal with shocks (Darnhofer et al., 2010).

System dynamics modelling (SDM) provides tools and techniques to further understand the long-term dynamics of food systems, that is, the feedback mechanisms, cross-scale linkages, cascading impacts and potential trade-offs arising from the system and policies interventions (Redman, 2014). Although system dynamics models have been built for agricultural and natural resources management issues in other parts of the world, our study pave the way for its applications in the Middle East North Africa (MENA) region and Morocco. Applying SDM in a country like Morocco, enable to explore the complex interplay between agricultural production, farmers' economic welfare and ecological preservation and highlights the interconnections within the three aspects of agroecosystems (Benabderrazik et al., 2021). Addressing systemic resilience of this socio-ecological system is of relevance as Morocco is increasingly exposed to climate disturbances such as droughts (Hirich et al., 2017).

Thus, we, here, explore how the concept of resilience to drought disturbances under different policies can be operationalized for an agricultural production system from a system dynamics perspective. We build on the methodology developed by Herrera and Kopainsky (2020) to apply it to the specificity of two tomato production systems in Morocco. We address more specifically the resilience of open-field domestic tomato producers and exporters producing tomato under greenhouses who are facing repetitive droughts and gradual groundwater depletion. In a first step, we clarify how resilience is operationalized with the use of SDM. In a second step, we use the system dynamics model to evaluate the implications of disturbances and longer-term natural resource depletion on both tomato production systems. Finally, we assess the implications of policies in both systems and discuss how they contribute to enhancing the resilience of the producers in the short as well as in the long run. The two policies that are explored in this study are (1) the desalinization of ocean water to release pressure on groundwater supply and (2) the re-use of treated wastewater for agricultural purposes.

2. A framework to operationalize resilience

Assessing and building resilience of agriculture to climate change has become increasingly important over the last decade. However, there is still no consensus on how resilience should be assessed and what indicators should be used (Brand and Jax, 2007; Douxchamps et al., 2017). Resilience is usually measured through the behavior of chosen outcomes from the system (e.g. groundwater volume, crop yield, farmers' cash flow, etc.) during and after the system has faced a disturbance (Tendall et al., 2015a, 2015b). Resilience is then understood as how this given outcome persists over time in the face of change and how it can transform into new more desirable configurations (Folke, 2006). For socio-ecological systems, SDM has been used to operationalize resilience and support the understanding of the long-term behavior of the system (Herrera and Kopainsky, 2020).

Building on the Walker et al. (2004) framework and the conceptualization in Herrera and Kopainsky (2020), we distinguish four types of behaviors, each described as resilience attributes in the literature (Fig. 1). Each of these resilience attributes are occurring, in this example, after a disturbance. They can be summarized as follows:

1. **Robustness** is understood as the capacity of the system to maintain its performance, despite a disturbance, without presenting a change in the performance of an outcome function (Herrera, 2017a). As depicted in Fig. 1, the outcome function does not necessarily operate constantly or linearly but is in a steady state. After a disturbance, the reference behavior of the function remains unchanged if the robustness is high.
2. **Adaptation** is characterized by the capacity to change the composition of inputs, production, marketing and risk management in response to shocks and stresses but without changing the fundamental structures and feedback mechanisms of the (farming) system (Meuwissen et al., 2019). The system bounces back to the reference behavior of the outcome function. Initially, the system “bends” as a reaction to the disturbance but eventually, the system adjusts its responses to changing external drivers and internal processes, and continues developing within the current stability domain (Berkes et al., 2008; Folke et al., 2010).
3. The third element of the resilience framework is **transformation**. Transformation happens when the system changes into a new system with a new structure and new feedback mechanisms (Herrera and Kopainsky, 2020; Meuwissen et al., 2019; Walker et al., 2004). After the disturbance and its effect on the function of the system, a transformative process could be engaged, leading the system to perform better than before the disturbance. Here, transformation is understood as the capacity to cross thresholds into new development trajectories (Folke et al., 2010).
4. A fourth development trajectory is when the system cannot sustain the disturbance and loose drastically its functionality, which could sometimes also lead to a “break or a **collapse**”. The disturbance becomes too strong for the system to engage into a resilience process, this is then an undesired behavior.

Complementarily to the three resilience attributes, a threshold needs to be defined between robustness and adaptation and between adaptation and transformation. In this regard, hardness metrics indicate the threshold between robustness and adaptation. The hardness of the system comes to test up to what degree a shock is not felt in the system, or more precisely what should be the amplitude of the shock before starting to feel the effects on the function of the system (Herrera, 2017b). Similarly, the threshold between adaptation and transformation or collapse will depend on the elasticity of the system, or its ability to withstand a disturbance and either bounce back to the original level of the function or change into a new development trajectory (Fig. 1). Accordingly, the system behavior changes from a regime A to a new regime B. In the case where there is no elasticity, the system

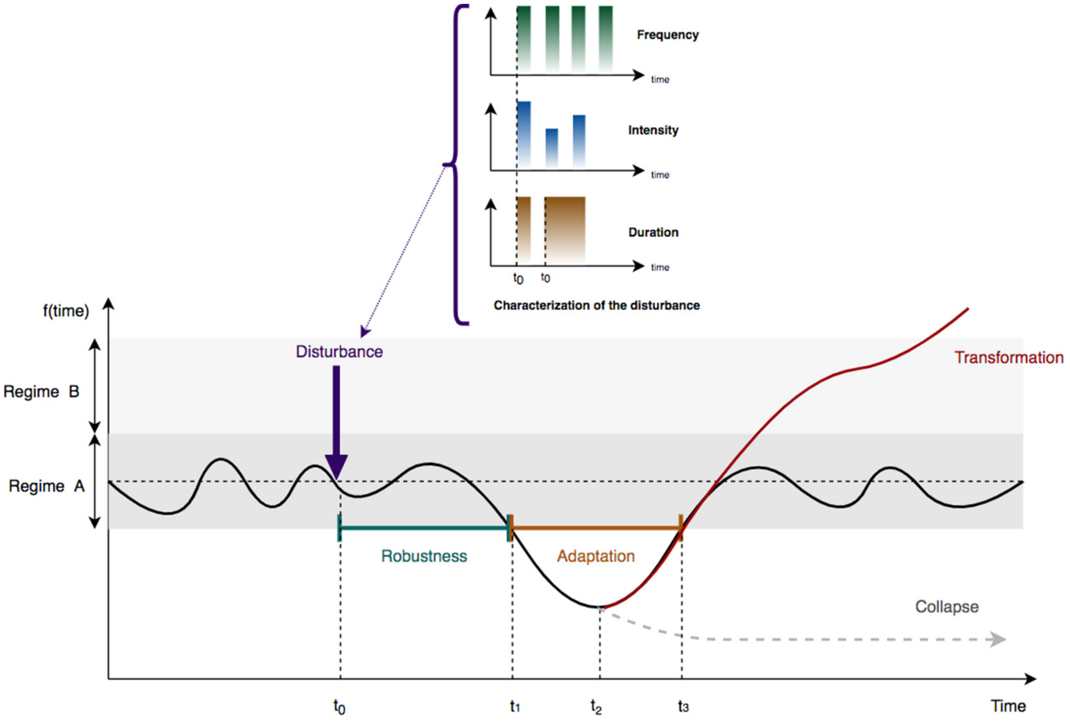


Fig. 1. Resilience framework – adapted from (Herrera and Kopainsky, 2020; Tendall et al., 2015b).

collapses. For modelling purposed the shock has been characterized by three parameters: (1) its frequency, as the occurrence of it happening along the model timeframe, (2) the intensity it has compared to an average norm and (3) the duration of the shock event.

3. Methods - system dynamic modelling

Recent studies suggest that SDM can be useful to quantify a system's response to disturbances and use causal analysis to identify ways to influence this response (Herrera, 2017a; Herrera and Kopainsky, 2020; Stave and Kopainsky, 2015). SDM draws upon both qualitative (e.g., survey and interview methods) and quantitative techniques (e.g., model simulations) and provides a valuable framework for investigating complex agricultural and natural resource management issues (Turner et al., 2016). SDM has been an approach used over the last 60 years for policy analysis and design (Sterman, 2018), and is particularly suited to analyze challenges arising from interactions, feedback mechanisms, circular causalities and interdependences. This approach fits to water management governance and has been used in several cases around to world, aiming to solve water crisis challenges (Barati et al., 2019; Turner et al., 2016).

The SDM process includes five main steps: (1) conceptualization, (2) dynamic hypothesis, (3) formulation of a simulation model, (4) testing and (5) policy design and evaluation (Rahmandad and Sterman, 2012). This five-step process serves as a basis to support an operational analysis of systems' resilience and to identify potential policies to enhance it. While a complete model description is found in Annex, here we report a simplified description of the main aspects of the model.

3.1. Conceptualizing the model

Elaborating and defining the main interconnections and feedbacks mechanisms of the system requires to conceptualize it first by answering the following question: “The resilience of what to what?”. The conceptualization of the model (see Fig. 2) is based on a series of expert interviews, field visits, a survey and an in-depth literature review. The following sub-sections are a summary representation of the model, further described in supplementary material. Tomato production system.

In Morocco, just like in many semi-arid and arid areas, groundwater-based irrigation could be considered as the most secure and reliable solution to provide access to water (Birkenholtz, 2014). It contributed to the intensification of existing farming systems and, subsequently, high-value crops such as citrus fruits, tomato, pepper and cucumber could be grown in Morocco (Ameur et al., 2017; Kang et al., 2009). Tomato, in particular, is a high value crop that nowadays plays an essential role in the daily Moroccan diet (Darfour-Oduro et al., 2018). Furthermore, tomato is one of the main agri-food export crops. Export production is mostly done under greenhouses in the Souss-Massa (SM) Region, while production for the national market is done in open-field in the northern regions of the country and mainly in the Rabat-Salé-Kenitra (RSK) Region. Hence, two typologies of producers exist (i.e., (i) export producers and (ii) local farmers) in the two mentioned regions, and are used throughout our analyses.

Over the last decade, extensive groundwater exploitation along with the recent droughts, have led to the over-exploitation of water resources (Alcalá et al., 2015; Bekkar et al., 2009). This overexploitation of water, coupled with intensifying droughts, inevitably has led to substantial decrease in water availability and to a degradation of water quality (Zouahri et al., 2014). These emerging issues generate cascading impacts on agricultural production itself and farmers' livelihoods (Gordon et al., 2010). For the purpose of this study, we focus mainly on the resilience of both typologies of tomato producers and more specifically on the effects of the disturbance (i.e. a drought) on their cash flow.

This study focuses primarily on the resilience of tomato producers to drought, with two case studies: open-field producers in the RSK Region and greenhouse exporters in the SM region. Producers' cash flow is considered as one of the economic indicators of the system. Moreover, the water volume in the aquifers is considered as one of the natural indicators of the system. In the following sub-section, the tomato production system is described.

3.2. Dynamic hypothesis

The first hypothesis about the system concerns its behavior regarding the yield function that is dependent on the water uptake and the use of other nutrients. The first reinforcing feedback loop (R1 in Fig. 2) is

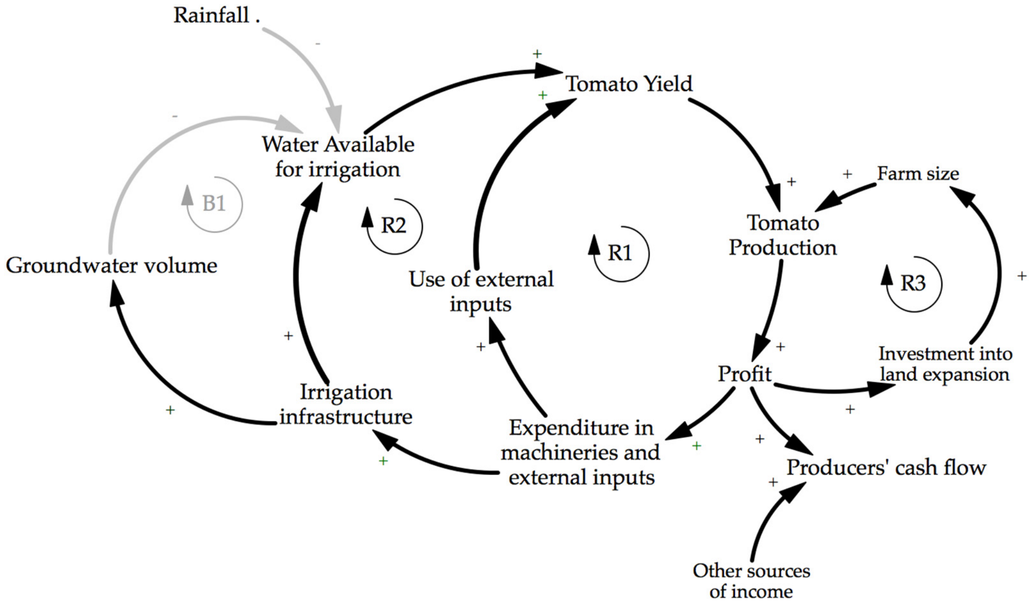


Fig. 2. Main feedback loops of the production system - linking yield and water uptake, to the water available and consumed in the groundwater table - grey arrows represent the negative causal links and black arrow represent the positive causal links.

described by the ability to reach a higher tomato yield when using and thus investing in external inputs (e.g. fertilizers, good quality seeds, etc.). A feedback loop is a sequence of variables and causal links that creates a closed ring of causal influences (Ford, 2019). The expenditure in machineries and external inputs are enabled by the profits from tomato production sales. Thus, the more tomatoes are produced, the more profits could be generated from the production and the more expenditure in machineries and external inputs could be done in inputs in order to increase the yield and the production. The reinforcing feedback loop (R3) operates in the same way as R1, the greater the profits, the more producers invest in expanding their farmland (this is more likely the case in the SM region). Complementarily, the second reinforcing feedback loop (R2) include expenditure in machineries and external inputs in irrigation and water inputs, as well as fertilizers, in order to maintain or increase the yield, until the yield plateau is reached. Fig. 2 is providing an overview of the general dynamics within the two production systems, open-field and greenhouse production. In both case studies, irrigation depends on groundwater and thus tomato production is controlled by the water balancing loop (B1). This means that (i) the more water is available in the aquifer for agricultural irrigation, (ii) the more water is used for agriculture, but then (iii) the less water is available in the reservoir. The yield function is dependent on the water uptake; hence the yield is considerably decreasing when the groundwater is depleting, generating cascading effects on the production and the profit. In the last decade, this reinforcing feedback loop (R2) has not been balanced by the water balancing loop (B1), which means that the groundwater volume has been used more than it has been recharged. In other words, B1 limits the yield growth mechanism in this system and the processes of groundwater overexploitation can then change the direction of R1 and R2 so that they turn from virtuous to vicious cycles. Hence, when a drought occurs, it affects several parts of the system such as an increasing groundwater consumption and a faster depletion, causing yield losses that appear to be faster and stronger in the long-run. An extended version of the subsystem diagram can be found in the annex, stocks with the in- and outflows are explained to enable a deeper understanding of the model main flows.

In the model, the drought is a lack of rainfall recharge to the groundwater table and the need for farmers to pump more groundwater to fulfill the water requirement of the agricultural crops. In the CLD, drought as a climate event is directly connected to the variable “rainfall”. For the resilience analysis, the main variables that will be looked at are “Groundwater volume” and “Profit” as proxy for water resources and producers' livelihood.

3.3. Formulation of the model - model development

The simplified causal loop diagram shown in Fig. 2 was translated into a formal computer simulation model that mathematically describes the dynamic interactions between tomato production, farmers cash flow and groundwater volume depletion (see Supplementary material). The quantitative data implemented in the model were extracted from an in-depth literature review. The data collection was complemented by a survey conducted among 244 tomato producers in both regions, aiming to capture the effects of the last drought producers faced in 2016 (Benabderrazik et al., 2021). The survey enabled to gather quantitative data to adjust the model. Moreover, it also constitutes a support for the model analysis and interpretation. The simulation model is at a high level of aggregation and, similarly to Costanza et al. (1993) or Gerber (2016), it allows the identification of leverage points, strategic areas of action and an understanding of the fundamental underlying mechanisms of the functioning of the two tomato production systems in Morocco.

In this study, the differentiation between fast and slow variables plays an essential role in the analysis. Slow variables, such as the amount of soil organic matter, shape how a fast variable, such as crop production, responds to variation in an external driver, such as variation in rainfall during the growing season. In that sense, natural capital stocks are considered as a slow variable (Walker et al., 2012) and defined as environmental stocks that provide a flow of various goods and services, such as soil, water, climate, food (Tallis et al., 2011).

For the purpose of this exercise, a couple of stocks were used and analyzed as slow variables of the system, such as water volume in aquifers and producers' cash flow. We see the analysis of the slow variables as a long-term assessment needed to understand the general behavior of the system over a long time period. Focusing on the arising delays within the stocks in the structural behavior of the systems can then lead to observe unintended consequences on the socio-ecological system.

3.4. Implementation of shocks - drought

The main focus of this study is to address the resilience of tomato producers to climate change. In this case, resilience is assessed for a specific disturbance. For the last decades, droughts have affected the country and agricultural productivity (Brahim et al., 2005; Esper et al., 2007; Karaky et al., 2016; Malki et al., 2017). During the 20th century, Morocco experienced several droughts of different durations and intensities and at various frequencies, with more than 10 major dry periods which extended over the entire country (Bazza et al., 2018). Droughts are predicted to happen more frequently and to affect agriculture and food security in the Middle East North African (MENA) Region and more specifically Morocco (Hirich et al., 2016; Le Page and Zribi, 2019; Schilling et al., 2012). Depending on the nature of the drought, increasing mean temperatures in all seasons, declining rainfall, and greater vegetation reference evapotranspiration will lead to decreased runoff, slower groundwater recharge rates and greater water stress (Babqiqi and Messouli, n.d.; Kmoch et al., 2018; Schilling et al., 2012).

Hence, we simulated different ranges and intensities of droughts for both regions and vary the intensity, the duration and the frequency of the droughts in order to observe the effects on both natural and economic indicators of the system (see Table 1).

4. Results

In the next step we aimed to simulate (i) how different ranges of droughts affect the system and the outcome functions (producers' cash flow and water volume in aquifer) (ii) how alternative water sources can decrease the pressure on the aquifer and (iii) how the policies would influence the resilience of tomato production systems and producers. For this purpose, the time horizons of the model extend from 2008 to 2050, the first simulated drought starts in 2016, which is t_0 in reference to the framework suggested in Fig. 1. The policies scenarios were conceptualized based on expert interviews and the official state strategy, suggesting alternatives ways to supply agricultural producers with irrigation water. The reference mode of behavior is a rapid depletion of groundwater table over the first decades, mostly because of intensive production – causing not only environmental damages but also social and economics, especially for smallholders.

4.1. Disturbances and drought impacts

Three different parameters of droughts were tested in the model: (1) frequency of the event (2) its intensity in terms of reduction of average rainfall and (3) the duration of the events (Table 1).

Firstly, the baseline behavior shows for both type of producers an increase in cash flow until reaching a tipping point between 2018 and 2020. Then, the cash flows start to decrease continuously for the open-field farmers and re-bounces only steadily for the export producers. This behavior could be explained by the link between water availability, crop production and cash flow from tomato profit (see Fig. 2). On the other hand, for both groundwater volumes, the baseline behavior shows a constant and fast decrease until 2023 and then stays at that minimal volume for the following decades. Secondly, the simulation of the two extremes cases of droughts (minimum and maximum values in Table 1) compared to the baseline scenario shows that the effects of droughts are, on the one hand, increased losses of producers' cash flow (Fig. 3) and, on the other hand, an accelerated depletion process of the groundwater volume (Fig. 4). Thirdly, the drought scenarios suggest that there are no endogenous mechanisms enabling adaptative behavior, as the simulated functions do not get to bounce back to the baseline behavior at any time. The first drought starts in 2016, as it was the last drought that the producers that we surveyed faced. In general, the behaviors are an acceleration of cash flow losses and groundwater volume depletion. Finally, groundwater volume appears to decrease shortly after the shock, showing no stability or general robustness for this outcome. From the lens of the resilience framework, set in Fig. 1, the groundwater volume directly shifts into a new regime (regime B), that could be defined as a water scarce regime. Yet, for the cash flow of both producer types, substantial changes only appear 2 years after the first shock and these changes are reinforced when the second shock occurs.

Table 1
Parameters used to characterize the disturbance affecting the system taken from Bazza et al. (2018).

Parameters of the droughts affecting the region	Average in the previous years, 1985–2014	Range considered for the simulation
Frequency (years between droughts)	2.5	Minimum 4 years Maximum 0.5 years
Intensity (% of average rainfall)	50 %	Minimum 10 % Maximum 100 %
Duration (years)	0.5	Minimum 0.5 years Maximum 4 years

4.2. Survey insights

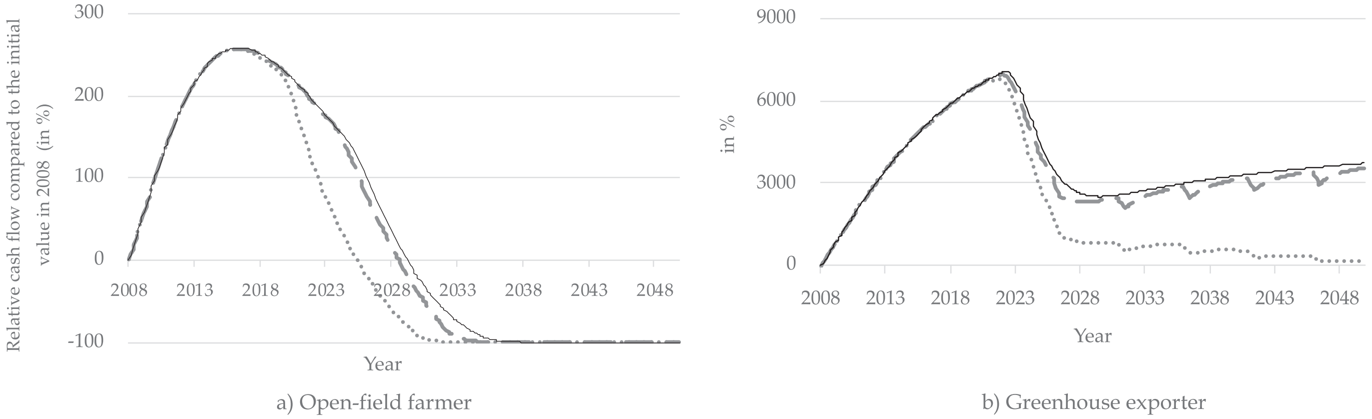
Results from the survey shows that more than 75 % of the producers perceived a decrease in water availability over the last years (from 2015 to 2018) and 54.9 % in RSK and 37.6 % in SM have experienced water shortage due to a drought (see Table 2). This shortage of water was observed when there was a lack of rainfall but also when more pumping energy was needed. Moreover, only minimal losses in production were reported during a drought, which shows that, in the face of droughts, the main reaction is to increase pumping. Indeed, up to 94.2 % of the producers in SM reported minimal or no losses, and 69.1 % in the RSK region. These results show, on the one hand, the significant difference between the greenhouse and the open-field producers. On the other hand, the results indicate the current robustness of the farmers in face of a droughts thanks to the irrigation infrastructures in place. By deepening the wells or equipping them with more powerful pumps, the groundwater table exploitation is accelerated in order to keep up with the water demand. On the other hand, 73.2 % in RSK have not implemented any drought resistance practices, while more producers have in SM (48.6 % of tomato producers). These results confirm the minimal reaction from the producers in terms of their production practices. Furthermore, observations from the survey depicts different coping practices between the types of producers; while in RSK region farmers change more easily into another crop production (e.g., pepper, cucumber, beans, etc.), in SM region the preferred response is to delay the planting time. Another support mechanism for 38.4 % of the surveyed export producers appears to be insurance, which is a service that only 1 respondent in the RSK region declared to have. Another leverage that could enact as a support, is being part of a peer network; 69 % of the exporters are linked to a group or a cooperative, while only 8 % of open-field producers are. Cooperatives and farmers groups can play a role in groundwater management, by generating common knowledge on the issues and the local dynamics and allowing to have a stronger voice in implementing irrigation policies (Fallon et al., 2019). These groups might then enable a better access to information regarding drought, that are reaching 68.8 % in the SM region and 56.3 % in the RSK region. While the decrease in groundwater water availability and the increase in drought events are inevitable in both regions, the reactions to these conditions are minimally oriented toward better agronomic practices at the farm level. Instead, producers appear to mostly rely on public institutions to support their water management through policies and infrastructures.

4.3. Policy implementation

Building on the model and its outcomes, we discuss the role of policy implementation in order to enhance the resilience of tomato producers in the face of different degrees of droughts. For each region a specific policy has been chosen according to the agricultural-water strategy planning (Dept. Finances, 2019). Each policy was then tested in the model and we quantitatively assessed their benefits using the resilience attributes: robustness, adaptation and transformation.

4.3.1. Policy 1 - groundwater and agriculture conservation through desalinization

Given the urgency of the situation in the Souss-Massa region, namely the alarming decline of groundwater table, a desalinization project was



a) Open-field farmer

b) Greenhouse exporter

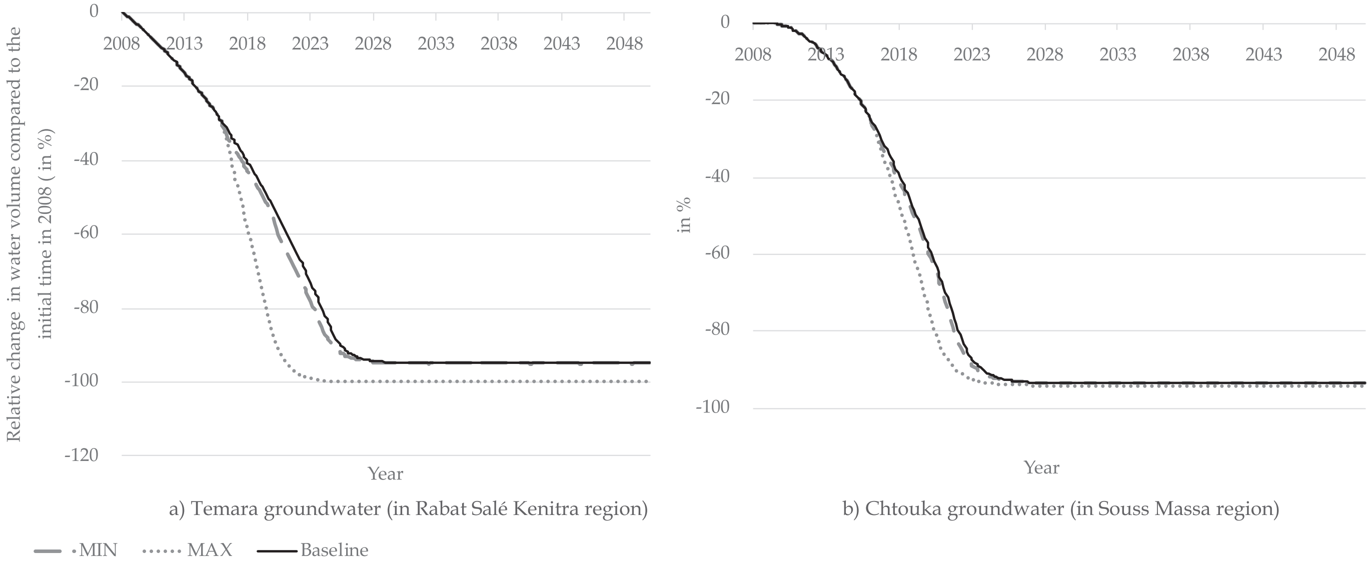
Fig. 3. Cash flow dynamics of open-field farmers (left) and exporters (right) – relative cash flow in % compared to the initial value in 2008 (solid line for baseline scenario, dashed line for minimal intensity drought scenario, dotted line for maximal intensity drought scenario).

initiated in 2011 (Allah et al., 2017). Desalination systems are presented as a solution for improving water supply in the Maghreb region (Sebri, 2017). The project was initiated as a result of increasing concerns by all stakeholders (producers, elected officials, local authorities, ministerial department, etc.) at local, regional and national level. Through a public-private partnership, aiming to build, maintain and manage the infrastructure and its exploitation, a desalinization plant is aiming to provide 3600 m^3 water per ha for all the producers willing to subscribe to the connection of this new facility. The project has already been launched and reinforced by the publication of a decree (N 6622-27 safar 1439 (16-11-2017)) aiming to support the protection of the water resources in Chtouka. Desalinated water should be provided to subscribers within the coming years – in the model the policy starts in 2020. These measures provide an exogenous change to alleviate the limits to growth imposed by the balancing feedback loop B1 (Fig. 2).

From a resilience perspective, the simulations in Fig. 5 shows the effects of the policy according to different ranges of drought (i.e. frequency, duration, intensity). For each drought, 50 simulations have been conducted within the ranges defined in Table 1. The first column in Fig. 5 shows the relative difference (in %) between the reference behavior and the outcome of the desalinization policy on greenhouse producers' cash flow. In the second column we look at the differences on groundwater volume, as the relative changes observed compared to the reference behavior presented in Fig. 4.

Results from the simulation show that for both groundwater volume and producer's cash flow the functions begin to cross the threshold that would characterize it as robust (e.g. more than 5 % relative changes compared to the reference behavior) 5 years after the first disturbance in 2021 (Fig. 5). This highlights how the internal dynamics of the system (i.e. groundwater depletion) are stronger than the external shocks in the early years. However, the repetition of the shock has a cumulative effect, that ends up exceeding the threshold limit.

Furthermore, the desalinization policy appears to serve as an adaptative measure against groundwater depletion. The exogenous supply of desalinated water enables a continuous supply of irrigation water for the farms and contributes to a momentary recharge of the water table (+150 % from the baseline scenario in 2033), until it reaches 0, back to the baseline reference in 2050. Scenarios with different ranges of droughts also show that for frequent droughts, of 6 months every year, the effectiveness of the policy could only last 12 years. The groundwater volume would then reach the baseline scenario state, in the late 2030s, which means a severely depleted aquifer. This return to the reference behavior of the outcome function is not a desired state, and implies, within the resilience framework, that the adaption process has not met its purpose, the system is then entering a



a) Temara groundwater (in Rabat Salé Kenitra region)

b) Chtouka groundwater (in Souss Massa region)

Fig. 4. Temara groundwater (in Rabat Salé Kenitra Region with open-field production - left figure) and Chtouka groundwater (in Souss Massa Region with greenhouse production - right figure) dynamics. Relative change (%) in water volume compared to the initial time in 2008 (solid line for baseline scenario, dashed line for minimal intensity drought scenario, dotted line for maximal intensity drought scenario).

Table 2
Survey findings reporting on drought effects and reactions.

	Rabat-Salé-Kénitra	Souss-Massa
	71	173
Water management		
Water availability - decreasing	76.1 %	77.5 %
Implement water harvesting technics	26.8 %	81.5 %
Experiencing drought		
Water shortage	54.9 %	37.6 %
Drought resistance practices		
None	73.2 %	48.6 %
Changing the crop	18.3 %	2.9 %
Delay in plantation time	7 %	12.7 %
Effects of drought on tomato production		
No loss	26.8 %	55.5 %
Minimal losses	42.3 %	38.7 %
Medium losses	18.3 %	5.2 %
Severe losses	9.9 %	0.6 %
Total losses	2.8 %	0.0 %
Access to information on drought	56.3 %	68.8 %
Insurance	1.4 %	38.4 %
Link to a group or a cooperative	8 %	69 %

potential collapse. These results also show that the system exhibit a worse-before-better (WBB) behavior. The short and long-term impacts of the policy are different; WBB is particularly problematic in sustainability contexts because of the long-time delays. In this case, it is explained by the dynamics of agricultural land use, which increases when there are no longer any water constraints, in the late 2020s. This is the consequence of the feedback mechanisms within the system, the more water is available the more producers will be able to generate profits and invest them into land expansion (see Fig. 2). This particular feedback mechanism leads to a policy resistance, where the desalinization process is not considered to be enough to tackle the issue of drought and groundwater depletion. These results suggest that a combination of water and land management should be implemented in order to prevent another groundwater depletion process starting in the early 2030s. Groundwater recharge is then only temporary and the critical state of the baseline scenario is reached once again 20 years after its introduction.

Lastly, from a producer's resilience perspective, the introduction of the policy enables a continuous supply of water and subsequently a maintenance of the crop yield and thus the revenue. Subsequently, the projection shows that according to the resilience framework, a transformation is occurring for producers' cash flow in this region. By securing yield production with a new source of water for irrigation, the policy withdraws the farmers to groundwater reliance. The same behavior could be observed no matter the ranges of the disturbance on the system, showing how effective this policy is for the export producers despite the rise in the price of water that this policy suggests. Based on the projections of the system dynamics model showing a return to low groundwater volume in 2040s, we question to what extent a desalinization project contributes in the long run to the sustainability of the system, and whether efforts for its implementation are justified in that sense.

4.3.2. Policy 2 – inter-sectorial link – wastewater reuse for agricultural use

The second policy we tested in the Rabat-Salé-Kénitra region, where open-field tomato producers can be found, is an inter-sectorial policy aiming to recharge groundwater table with treated wastewater from close urban areas. Given the necessity to intervene, policy-makers have directed their attention toward non-conventional water resources, such as recycled wastewater, to meet the demands (Hirich et al., 2017). Water recycling would be of great benefit for several purposes, such as agricultural and landscape irrigation, industrial processes, and recharge of groundwater table (Ait Brahim et al., 2017; Jaramillo and Restrepo, 2017). In Morocco, the ratio of treated wastewater to produced water was 24 % in 2017 (Frascari et al., 2018). Rabat-Salé-Kénitra region is dedicated to intensive land use for growing vegetables for national consumption purposes in a peri-urban agricultural zone. Thus, the potential of urban wastewater reuse is substantial and could lead to decreasing the pressure on the aquifer. This is particularly relevant as the groundwater in the Temara region presents a high risk of salinization (Zouahri et al., 2014). For this purpose, the goal of this policy test is to use treated urban and industrial wastewaters for agricultural purposes in order to lower the pressure on the groundwater table.

In Fig. 6 show the effects that the policy had according to different ranges of drought (i.e. frequency, duration, intensity). The first column shows the difference between the reference behavior and the outcome of the wastewater reuse policy on open-field producers' cash flow. This is presented in Fig. 6 as the difference in cash flow (in MAD, where 10 MAD = 1 USD) generated by the policy and the drought ranges. In the second column we look at the differences on groundwater volume, as the relative changes observed compared to the reference behavior presented in Fig. 4.

In a first place, with a hardness fixed at ±5 % (Annex) and the first drought starting in 2016, the robustness of both of the outcome functions in this region appears to be higher than the system in the SM region (Fig. 6). The threshold is crossed in 2025, when the duration of the drought remains lower than 2.4 year and after. However, if the duration is longer than 2.4 years, the system starts to react significantly (beyond 5 %) and the robustness limit is reached in 2020. Regarding water volume, the policy enables a slow and steady recharge of the groundwater. In 2050, the groundwater volume is predicted to reach 200 % of the reference behavior. However, we know that by 2050 the critical level of groundwater volume has been reached (Fig. 6), although the policy plays an encouraging role in supporting groundwater recharge, it is not significantly transforming the alarming situation.

The simulation shows that the policy allows open-field farmers to expand their cash flow (Fig. 6). Thus, if initiated within the next 2 years, this policy would enable a delay in farmers' impoverishment for some 20 years, until 2040. In the sense that the exogenous water supply changes the reference behavior of this outcome function, until it returns to it. While different ranges of frequency and intensity of the drought operates similarly, the duration of the drought (in brown in Fig. 6) plays a significant role for producers' adaptative process.

When the drought is longer than 1.4 years, then the policy could not play a significant role in supporting producers' livelihood, a longer drought duration would hinder more cash flow outcome, despite the implementation of the policy. To that extend, the implementation of this policy also needs to be combined with complementary interventions in order to reduce the potential impacts of a long drought on producers' cash flow. Among these complementary adaptive measures, local actions like the enhancement of water management practices and diversification of income could be combined with regional and national actions like securing market structure and prices.

However, installations for recycling wastewater take time to build and institutional authorities must take the lead on this policy before it becomes too late for the producers. On the other hand, the use of treated wastewater in agriculture is not exempt from adverse effects on the environment, especially on soils. The scientific literature includes evidence of alterations in the physicochemical parameters of soils (Jaramillo and Restrepo, 2017). The maintenance of a rich and diversified autochthonous soil microbiota and the use of treated wastewater with minimal levels of potential soil contaminants are proposed as sine qua non conditions to achieve a sustainable wastewater reuse for irrigation (Becerra-Castro et al., 2015). This means also that more agronomic practices have to be implemented at a farm level to mitigate potential negative effects of this policy. Findings from the survey show that agronomic practices are still limited, especially for open-field farmers. Finally, this measure is a way to contribute to a dialogue on how inter-sectorial management methods are crucial to tackle agricultural issues and create a bond between the agricultural sector and the urban areas, decompartmentalizing the institutional options.

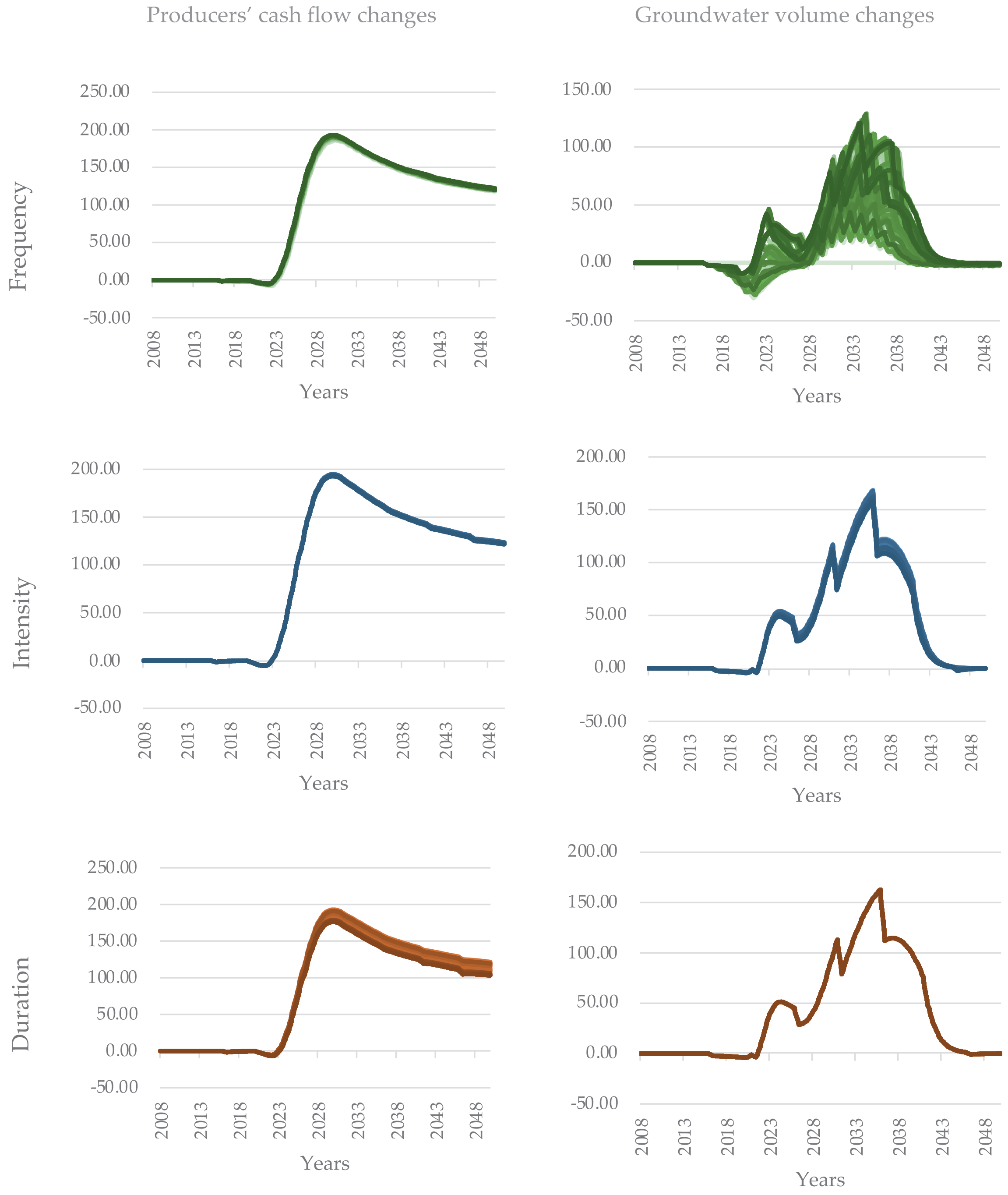


Fig. 5. Desalinization policy effects in the SM region on producers' cash flow (left) and Chtouka groundwater volume (right) - relative changes in % compared to the baseline scenario for different ranges of drought frequency (in green), intensity (in blue) and duration (in brown) – see ranges in Table 2.

5. Discussion

5.1. Operationalizing resilience

With a focus on two tomato production systems in Morocco, we operationalized climate resilience using a system dynamic model. Within a defined resilience framework, based on research in socio-ecological systems resilience (Helfgott, 2018; Herrera, 2017b), we aimed for a deeper understanding on the driving dynamics of the system and the effects of a climate related shock for natural resources and producers' livelihood. The policy scenarios guided the reflection on ways to enhance the resilience. The added value of the model-based approach allows a unique view on the driving dynamics and the feedback mechanisms that arise during the policy implementation. The results show that the two policies could prevent aquifer depletion, for a certain time, and enable farmers to have continuous access to irrigation. The long-term simulations, however, highlight policy resistance mechanisms as well as a worse-before-better behavior. As a result, the short-term positive impacts of the policies bounce back to the original situation in a longer time period, either for the natural resources (i.e. for policy 1 - desalinization) or for producers' livelihoods (i.e. for policy 2 - wastewater reuse). As an example, in the SM region the aquifer starts declining again 15 years after the launch of the desalinization policy (Fig. 5). On the RSK region, the producers' cash flow starts declining in 2031, 8 years after the launch of the inter-sectorial policy (Fig. 6). The systems performance is dependent on a multitude of interactions and the model helps to clarify these interactions more explicitly.

Fig. 6. Inter-sectorial policy scenario for the RSK region – on the left - farmer's absolute cash flow difference (in Moroccan Dirham - MAD) and on the right - Temara groundwater volume relative changes (in %) compared to the baseline scenario for different ranges of drought frequency (in blues), intensity (in green) and duration (in brown) – see ranges in Table 2.

As of today, only the desalination policy has been already launched and will be ready to start in 1–2 years, supporting mostly the exporters. To our knowledge, a wastewater treatment plant has not yet been initiated for the RSK region, threatening not only the long-term but also the short and mid-term prosperity of open-field producers. Moreover, the predicted increase of drought frequency and intensity in the future will speed up the aquifer depletion and reinforce negative effects on yield and farmers savings, leaving the farmers with no sustainable and resilient solutions for the future.

5.2. Temporal and spatial dimensions of resilience

Multiple spatial levels are tackled in this study such as the farm, local groundwater table, different market access (local and global) and agricultural strategy. The interconnection between these levels is crucial to be taken into account. Water depletion dynamics arise from a behavior engaged by all the farmers using the same aquifer, which is supported by the national agricultural strategy. Results from the survey suggested that at a farm scale farmers are not subject to high yield variation yet, nevertheless, the model shows on a bigger scale that the actual depletion of groundwater volume is occurring; and is even faster as droughts hit the regions. The particularity of this system is that there is a need for a common understanding of the water management challenges to face it in a long-term. Therefore, farmers can not merely address this situation individually. The temporality of the simulation allows also to gain insights in the overall sustainability of the systems. As a matter of fact, policy resistance mechanism appears after one or two decades and the model illustrate how the policies act out as a delay toward an undesirable state. Along these lines, we dissociated and analyzed slow variables to get an idea of the delays generated by changes and the behavior in the long run. The simulations underline the need to combine resilience and sustainability in this socio-ecological system. Sustainability appears to be a necessary pre-condition for a resilient system. Farmers' livelihoods are considered resilient and sustainable only when farmers can adapt or transform their capabilities while not undermining natural resources (Ifejika Speranza et al., 2014). Under rapid and complex changes in environments, societies and economies, a pathway to sustainability becomes essential for ensuring that human livelihood is sustained, social equity is ensured, and environmental integrity is protected (Fiksel, 2015; Leach et al., 2010). In this case, a sustainable outcome is taking into account, on one hand, natural resource regeneration, and on the other hand, a long-term viable situation for producers, in particular open-field ones that appear to be more vulnerable in the course of the next decades. In relation to resilience theory, sustainability is a distinct but complementary concept, crucial to deal with future challenges and disturbances of the agricultural system (Redman, 2014). Sustainability and resilience are inextricably linked to each other (Tendall et al., 2015a) and need to be considered jointly (Carpenter et al., 2014), as they both have many common objectives. In this study, we comprehend resilience as a component of sustainability (Marchese et al., 2018). In other words, resilience refers to the maintenance of natural capital in the long-term in order to provide ecosystem services that provide instrumental tools for supporting human society (Brand and Jax, 2007). This study shows how inextricable those two concepts are in face of climate related shocks, resilience assessment must be conducted taking into account long-term outcomes of the system.

5.3. Accountability for building resilience

Within a context where building climate resilience for farmers in the long run becomes imperative, it becomes crucial to identify who takes accountability for it. In this study, the policies presented in the Results section have the particularity of being strongly supported and led by the state. However, the survey shows a deficit in water management accountability. In the case of Chtouka groundwater, the desalinization policy has emerged from the participation of various stakeholders of the food systems and enabled to quickly identify a solution to the groundwater depletion. On the other hand, for a similarly alarming situation in the Temara aquifer, no community driven projects have emerged to face water and climate pressures. Additionally, the reference behavior shows that open-field farmers from the RSK region strongly depend on the aquifer and are in a more vulnerable position in terms of cash flow dynamics. Further aspects need to be addressed such as stakeholder representation, the distribution of authority (formal or informally) and mechanisms of accountability. Mechanisms of accountability are especially important when the access or use, of natural resources are being reallocated or negotiated. By identifying critical obstacles and opportunities in the governance context, researchers and development practitioners can better support efforts to strengthen livelihood resilience, and to transform the institutions that reinforce poor people's marginalization and vulnerability (Ratner et al., 2013). Building the capacity of farmer communities is a crucial attribute to enhance the resilience of their farming systems.

5.4. From descriptive to normative resilience

Our descriptive resilience assessment shows how the behavior of the farming systems could be robust, adapt or transform compared to a reference behavior. Within such context, the effect of the desalinization policy enacting like an adaptative measure on the groundwater volume, is not a required outcome because the volume reaches the reference behavior after 20 years. In this case, the combination of desalinization together with land use management is required to stop the expansion of the production area and the continuous overexploitation of the groundwater. Similarly, the second policy requiring inter-sectorial links, is enacting like an adaption measure for producer's cash flow. After 10 to 20 years generating more revenue, the producers reach back to the initial projected cash flow, which is particularly low. These two adaptation schemes do not constitute a desired outcome neither for water conservation nor for producer's livelihood.

To measure the resilience of the system one needs to characterize the nature of its response to a particular disturbance, from a particular perspective over a specific timeframe – in other words, framing the system is key (Helfgott, 2018). The application of SDM enables to draw clear boundaries on the different levels, timeframe and outcome we want to consider. In this case study, the outcomes of the policy implementation highlight the necessity to be more critical in the resilience assessment and to shift from a descriptive analysis to a normative perspective (Brand and Jax, 2007; Helfgott, 2018). The desired reference behavior such as the recovery of the natural resource, in this case groundwater volume, must be included in governance strategies, just like the perenniality of the agricultural activity for open-field producers. Leaning toward a normative resilience approach, should include long-term management of the socio-ecological system.

6. Conclusion

We described the development of a system dynamics model (SDM) that captures the interactions and feedbacks in two regions and for two types of tomato producers in Morocco. The specific objectives of the study were to use the model as a learning tool to improve our understanding of the long-term dynamics of the different production systems and as a basis for exploring alternative policy scenarios for a sustainable and resilient water resource management and agricultural development. We demonstrated that SD is a useful tool to understand the feedback mechanisms, long-term behavior of the systems and their reactions to different ranges of sudden changes. The model-based approach enabled us to highlight the policy resistance mechanisms and further discuss on ways to overcome these foreseen challenges. In addition, it constitutes an insightful decision support tool for sustainable water resources and agricultural management.

By presenting the outcomes regarding the natural resource management (e.g. groundwater volume) and tomato producers' livelihoods (e.g. Farmers' cash flow), we draw attention to their strong linkages, the need to contextualize the driving dynamics and the need to build resilience with a systemic approach. Enhancing socio-ecological resilience has to be intrinsically linked to building the capacity of these communities. In this case, the restoration of natural resources or ecosystem services must be part of the desired system. Once the desired outcome is also acknowledged within the governance strategy, the system could then lean toward a more sustainable and inclusive resilience beneficial for the commons.

CRediT authorship contribution statement

Kenza Benabderrazik: Writing – original Draft, Conceptualization, Methodology, Software, Formal Analysis, Funding Acquisition

Birgit Kopainsky: Supervision, Writing – Review & Editing, Conceptualization, Methodology, Software, Formal Analysis, Validation

Elena Monastyrnaya: Writing – Review & Editing, Validation

William Thompson: Writing – Review & Editing, Validation

Lina Tazi: Resources, Investigation, Writing – Review & Editing, Validation

Jonas Joerin: Investigation, Writing – Review & Editing, Validation

Johan Six: Supervision, Writing – Review & Editing, Funding Acquisition, Validation.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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