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Agricultural intensification can no longer ignore water conservation – A systemic modelling approach to the case of tomato producers in Morocco

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ABSTRACT

Agricultural-food production systems are facing the challenging task to provide food and socio-economic welfare while preserving natural resources in the long-term. In Morocco, the Green Moroccan Plan steered the promotion of groundwater-based drip irrigation. Over the last decade, the Plan encouraged producers to shift to cash crop production. This is how tomato became a main agri-food export commodity mostly produced in greenhouses in the Souss-Massa region and produced intensively in open-fields for local demand in the Northern part of the country. However, water resources are expected to become particularly scarce over the next decades, increasing the vulnerabilities of tomato farmers in face of unforeseen changes and shocks. The main purpose of this study is to show a) how global and local tomato value chains respond to irrigation schemes and b) what the environmental consequences are. By means of a system dynamics model, and a survey conducted among a sample of 244 producers, we describe and outline the major interactions between agricultural, ecological and socio-economic dimensions of the tomato production systems. The results of the model simulations highlight how over-exploitation of groundwater tables negatively affects crop production and farmers' welfare. The model shows that in the near future, water scarcity will have long-lasting consequences on the producers, such as reduced productivity and losses in cash flow. Our model results highlight that measures need to be taken in the coming years in order to prevent the predicted irremediable water shortage in 2030. We conclude that the current groundwater management will, in the long-term, lead to irreversible groundwater depletion which will enhance already existing inequalities between the two types of producers. Urgent actions have to be taken in order to sustainably manage water while supporting farmers in the long-term.

1. Introduction

Designing policies that ensure food security, support social and economic welfare and at the same time preserve natural resources in the long-term is challenging. Historically, the prospect of economic growth coupled with agricultural intensification has led to the unsustainable use of resources and environmental degradation in several countries (Alauddin and Quiggin, 2008; Gohari et al., 2013; Xu, 2001). Today, long-term effects of some policies, such as deepening socio-economic inequalities and degradation of natural resources can be observed (Manero, 2017). These effects are further exacerbated by climate change and market instabilities, among others (Ouraich et al., 2019; Rochdane et al., 2014). Those incremental stresses can lead the system to a regime shift that may evoke large, unexpected changes in ecosystem services and human livelihoods (Scheffer and Carpenter, 2003). To avoid unanticipated consequences of agricultural policies in the future, such as the dependency of some food systems on subsidy programs (Gerber, 2016), it is crucial to investigate the dynamics arising from the complex interrelationships in food and farming systems.

In countries facing increasing water scarcity, suitable water management and more particularly water-savings in agriculture becomes a necessity. Over the last decades, governmental water agencies in these countries have encouraged farmers to shift to localized irrigation methods, such as drip irrigation, to save water. Groundwater-based drip

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irrigation appeared to be the most secure and reliable solution to provide access to water, especially in semi-arid and arid areas (Postel et al., 2001). The combination of drip irrigation and trade policies has fostered the intensification of existing farming systems and, subsequently, high-value crops (Ameur et al., 2017; Kang et al., 2009), such as fresh fruits and vegetables. This contributed to the rapid expansion of agri-food export production and global food value chains (Akesbi, 2014). Paradoxically, the conversion to drip irrigation and the shift in cropping patterns has increased the water consumption in Morocco (Molle and Tanouti, 2017a). The extensive groundwater exploitation along with the recent droughts, have led to over-exploitation of water resources (Alcalá et al., 2015; Bekkar et al., 2009). Thus, the design of water resource management policies requires an integrated perspective that considers biophysical and socio-economic aspects, as well as potential feedbacks associated with the introduction of such policies (Batchelor et al., 2014; Berbel and Mateos, 2014).

In the agricultural-food production systems, operationalizing the interactions between disparate measures of productivity and sustainability necessarily requires an adequate understanding of the complex interactions between environmental, social, and economic drivers. Socio-ecological systems (SES) contain a multitude of diverse components, interacting non-linearly and dynamically in both space and time (Walters et al., 2016). More specifically, for water resources management systems, it has been argued that the inability to develop sustainable solutions is grounded in the lack of understanding about the interconnections and dynamics of different sub-systems (Davies and Simonovic, 2011; Kotir et al., 2016; Sivapalan and Blöschl, 2015). System feedbacks are key mechanisms that influence the sustainability of social-ecological systems. The system dynamics modelling (SDM) approach offers a way to gain understanding of an interconnected and complex systems behavior over time and its non-linear feedback mechanism (Kopainsky et al., 2017; Turner et al., 2016). This modeling approach is also a tool to support the design of policies or strategies for improving system performance over time (Kopainsky et al., 2012; Kopainsky and Luna-Reyes, 2008; Sterman, 2001). Several recent studies have used the SDM approach to develop system dynamic and simulation models in various agricultural systems, such as understanding the role of Fertilizer subsidy program in Zambia to increase maize availability or analyzing food security resilience to climate change in Guatemala (Alifujiang et al., 2017; Cheng et al., 2018; Gerber, 2016; Herrera, 2017; Xu, 2001). The diversity of SDM applications contributed to an improved understanding of the current and future dynamics of water resources management systems for several contexts, such as exploring policy scenarios for sustainable water resource management and agricultural development in the Volta region in Ghana or develop smart groundwater governance in Iran (Barati et al., 2019; Kotir et al., 2016).

The tomato production in Morocco allows us to explore the complex interplay between agricultural production, farmers' economic welfare and ecological preservation. It becomes relevant to further investigate what are the synergies and trade-offs between those three aspects of agroecosystems. Hence, with this study, we aim to understand the consequences and the cascading impacts on the socio-ecological systems of the irrigation schemes for both global and local tomato producers by using SDM to evaluate the cascading impacts of irrigation on the sustainability of these agricultural systems. More concretely, we seek to answer to the question – what are the different socio-ecological implications of the Green Moroccan Plan of both natural resources and humans. Using SDM enables to highlight the interconnections within this socio-ecological system, drawing those linkages become then crucial to investigate the disparities between several groups of producers.

The first section of the paper provides an in-depth description of the case study and its specificities, based on a literature review and interviews with experts. Then, we present a social-ecological system (SES) model and describe the main modules composing the model. Using this model, we analyze the long-term effects of the system, with a status-quo scenario. Finally, we analyze the outcome of the model and identify the implications of the agricultural irrigation and production strategies with a special focus on the outcomes for agricultural production, producer's economic welfare and water resources. We chose SDM as a coherent and relevant approach for analyzing complex SES behavior (Balali et al., 2015; Stave and Kopainsky, 2015).

2. Water governance and a dual agricultural system

2.1. Agricultural strategy and water governance

In 2008, the Moroccan government launched an agricultural strategy, the Green Moroccan Plan (GMP), to rehabilitate agriculture and turn it into the main engine of economic growth and a tool against poverty in Morocco. This strategy was based on two pillars and was expected to reach both large and small actors along the agricultural value chains. The first pillar of the strategy aimed to promote modern agriculture, with high added value crops adapted to export markets. The second pillar aimed to develop an approach to fight against poverty by significantly increasing agricultural income for the most vulnerable farmers, particularly in disadvantaged or peripheral areas (Plan Maroc Vert, 2008 (Akesbi, 2012)). Moroccan agriculture has essentially been shaped and divided by these two pillars. The differences between these two systems became particularly visible in the fruit and vegetable sector, with 517 thousand tons of fresh tomato exported, making the crop one of the flagship products for export (FAOStat for 2017). Among other targets, this latter strategy aims at converting 50% of the Moroccan irrigated agricultural land area by 2020 to drip irrigation through a national subsidy program (Alonso et al., 2019). However, over the past decade, the expected results of this strategy, officially ending in 2020, have been widely disputed (Akesbi, 2014; Faysse, 2015; Ouraich and Tyner, 2018; Sippel, 2016). Previous studies argue, on the one hand, too much focus on agricultural intensive practices and productivist models to the expense of natural resources preservation. On the other hand, the subsidies conversion to drip irrigation and the expansion of intensive farming had severe impacts on water contrary to what was announced. The latter underlines the need to integrate major challenges related to water management or global competitiveness (Boudhar et al., 2017; Schyns and Hoekstra, 2014).

2.2. A dual production system

The diversity of horticultural production systems, for tomato especially, ranges from open-field grown systems to greenhouse production systems (soil or soil-less culture) (Georgios K. and Maximilin, 2017). In Morocco, exported tomatoes are produced in greenhouses that are extensively mechanized and generates a yield from 120 to 250 t ha^{-1} (wet weight). This system benefits from better connection to processing industry and cooperatives that ensure conditioning of the crop and access to export markets. Around 85% of total tomatoes destined for export are produced in the Souss-Massa region (OMRVASM, 2015). Considered as one of the most important agricultural poles, 55% of the exported fruits and vegetables are produced in this region in order to meet the European off-season demand (from September to May). This semi-arid region is characterized by a low average rainfall of 200 mm $year^{-1}$ and average temperature of 24 ºC (Ait Brahim et al., 2017; Malki et al., 2017). The high-water demand for the crops has led to the over-exploitation of groundwater for irrigation purposes. The Chtouka aquifer located in the region has recorded an annual deficit of 58–60 Million m^3 per year over the last two decades (Hirich, 2016; Malki et al., 2017). Agricultural productivity has subsequently increased groundwater resources depletion and degradation rates over the last decades (Payen et al., 2014). Due to its strategic economic and political importance, the region has been extensively studied over the last decades and quantitative information on the water and agricultural situation is available in the scientific and grey literature. Several studies (Ait Brahim et al., 2017; Malki et al., 2017) showed the groundwater depletion patterns as well as its impacts on the quality of the water.

In contrast to large export producers, smaller producers are growing tomatoes in irrigated open-fields (from April to October) along with other vegetables throughout the year, generating lower yields from 40 to 80 t ha^{-1} (see Fig. 1). For clarity reasons, open-field smaller producers will be referred to as farmers in the following sections. According to the data provided by the ministry of agriculture, the Rabat-Sale-Kénitra (RSK) region has produced most of the irrigated and open-field tomatoes in recent years, 73 thousand tons in 2017 (DSS, 2017). RSK is considered as one of the most important areas for fresh fruit and vegetable production. Such production, using drip-irrigation has fostered extensive groundwater exploitation. For the RSK region, we found no studies reporting quantitatively on the depletion of the resources, however, several studies on Morocco and regions close-by reported on the groundwater over-exploitation and the subsequent issues regarding water quality and availability (Hirich, 2016; Malki et al., 2017; Najib et al., 2016).

3. Material and methods

3.1. Simulation approach

To investigate the dynamic interactions within the chosen agricultural system, we developed a system dynamics model (SDM) representing the Moroccan tomato SES. According to Repenning (2002), there are, two corresponding benefits for the approach to mathematically represent an SES as an SDM. First, a model allows to implement the internal consistency of the theory and ensures that the behavior it purports to explain can in fact be generated by its underlying assumptions. Second, a model can serve as a sort of a "laboratory" to test different scenarios into the future. Thus, we developed a SDM model to understand the dynamic interactions between tomato production, farmers welfare and groundwater depletion. The dynamic behavior arises through a non-linear interaction of feedback loops connecting the three following components: ecological, agricultural and socio-economic (see Fig. 2).

3.2. Data collection

The following four-step procedure allowed us to capture the specificity of this SES, to observe the cause-and-effect relationships as well as the feedback loops within the system and to gather information for a quantitative representation.

First, an in-depth literature review was conducted to develop a modeling framework. The framework allows illustrating the system's structure and feedback mechanisms (Sterman, 2001). Furthermore, the literature review allowed identifying, how systems' components influence each other, i.e. the polarity of the causality which is essential in understanding system's behavior. Also, we identified drivers that leads to perturbations of a loop that may then amplify the original effect (a reinforcing loop, R) or into an equilibrating response (a balancing loop, B). This first step led to the description of the model through a causal loop diagram.

Second, we conducted a series of expert interviews and several field visits, which allowed more empirical observations. For the interviews, we used a semi-structured approach, which allowed us to validate and quantify the causalities established through the literature review in the first step and also to identify the specificities of the tomato production system. The interviews were conducted with agricultural consultants, delegates of the Ministry of Agriculture, Fisheries, Rural development, Water and Forests, academics, farmers and farmers cooperatives (see Table 2).

The first two steps allowed us to establish a modeling framework that is a qualitative statement about a system's structure. Consequently, in a third step, this framework was further used as a base for developing and calibrating the quantitative simulation model. To get quantitative data to adjust the model, a survey among 244 producers was conducted, in spring 2018 (see Table 1). The fourth step of the data collection was based on the formal mathematical simulations run on the modelling framework. Technically, the model consisted of a set of coupled, non-linear, first-order integral equations. Once the model was calibrated and validated (see Appendix), it was used to test the sensitivity of some key indicators and served as a "virtual playground" in which to test different experiments and scenarios, from agricultural management practices to policy implementations. The full model was designed using Vensim software (Ventana, 2015).

3.3. Survey outcome

The survey informed us on the specificities of the 2 typologies of tomato producers, and provided basic information such as average yield in recent seasons, farm size, area allocated for tomato production, irrigation infrastructures, links to markets, participation in cooperatives and access to other social support. Moreover, the results of the survey provided support for the model analysis and interpretation.

Complementary, the survey conducted in 2018 shows the main characteristics and differences between the two types of producers. Firstly, drip irrigation system is used by all producers surveyed, water is entirely supplied from wells in the RSK region and in SM region 31% of the producers also use well. However, the majority of producers extract water from boreholes, highlighting there need to pump at deeper level to have access to water. Then, results from the survey indicate that for open-field farmers water management practices, such as water harvesting techniques are not applied (see Table 2). Only 9.9% are mulching there fields, while it has been shown in other Mediterranean context that mulching reduces the water footprint of crops more than drip irrigation, and when those two practices are combined the effects on water conservations are higher (Nouri et al., 2019). Water harvesting techniques are also a key farm management practice to integrate in order to minimize water intake from the groundwater table. Some farmers surveyed have reported the use of semi-circular bunds as a way to collect water run-offs an increase soil moisture. In the same perspective of increasing the water retention capacities of the soil, some farmers have reported the use of compost that is furthermore used as a source of organic fertilizer. Increasing soil moisture could thus influence positively the recharge of the aquifer. However, farmer's lack of accountability in water management on the field have been reported in

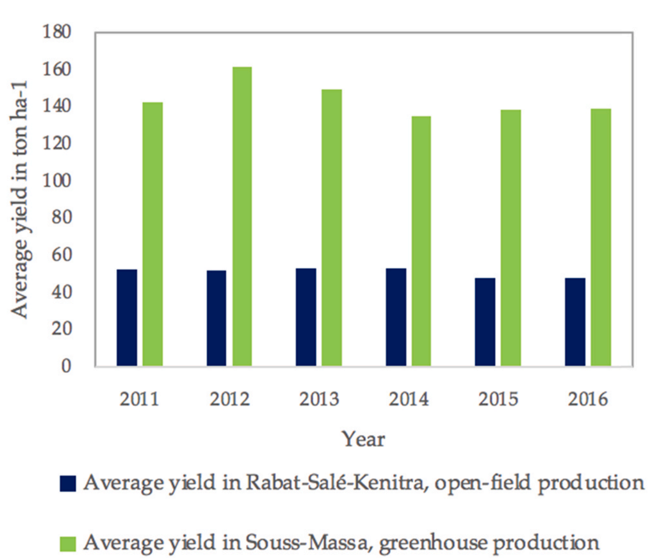

Fig. 1. Average yield in the two regions from 2011 to 2016. Data provided by the Ministry of Agriculture.

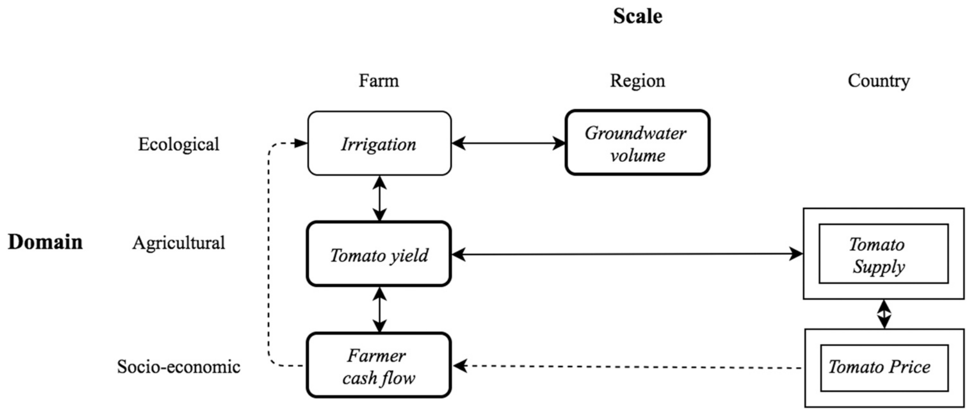

Fig. 2. Interactions within the tomato production system – boxes in bold represent the stocks used in the model, boxes with double lines are common variables between exporters and farmers, straight arrows are the direct connections between elements and dashed arrows are the indirect connections between elements.

Table 1
General overview of the producers' characteristics in the Souss-Massa and Rabat-Sale-Kénitra region in spring 2018 followed by the sample of stakeholders selected for semi-structured interviews. Numbers indicate the number of stakeholders interviewed, m stands for male and f for female. The interviews comprised 24 persons, 15 in the Souss-Massa Region, 9 in the Rabat-Sale-Kénitra Region.

	Souss- Massa Region (Greenhouses)	Rabat-Sale-Kénitra Region (Open fields)
Number of observation (#)	173	71
Average farm size (ha)	13.7	3.4
Average Tomato field size (ha)	11.3	1.1
Average Tomato yield (ton/ha)	188	56
Using drip irrigation (%)	100	100
Stakeholders interview		
Greenhouse producers	8 m	
Open field producers	1 m	2 m
Cooperative delegates	3 m	
Exporter association	2 f,1 m	
Input suppliers		1 m
Academia		2 m
Agricultural extension officer		1 m
Agroeconomics consultant		2 m

Table 2
Summary of the main findings of the survey (in %) conducted among 244 producers in Rabat-Salé -Kénitra and Souss-Massa.

	Rabat-Salé - Kénitra Region	Souss – Massa Region
Number of observations	71	173
Soil and Water management practices		
Type of irrigation system	Drip irrigation	Drip irrigation
Source of Water		
Borehole	0	58
Well	100	31
Rainfall	77	–
Water harvesting techniques	0	42
Crop rotation	71.8	5.8
Mulching	9.9	52
Price and Market		
Tomato is the main source of income	58.6	96.4
Growing other Fruits and vegetables	100	33
Alternative sources of income - Non-Farming (Seasonally)	21.1	1.2
Alternative sources of income - Non-Farming (yearly)	9.9	6.4
Price fixation through cooperatives	0	30
Link to a market		
Export Market		79
Local and Regional Market	100	98

other studies (Bekkar et al., 2009). The slow dynamics arising from groundwater exploitation can compromise farmers acknowledgement of the scope and urgency of the threat in the long run.

Secondly, the survey results indicate that tomato production is one of the main sources of income for both type of producers, with 96.4% of the producers considering tomato as their main income source in SM region and 58,6% in the RSK region. Thus, 100% of the open-field farmers grow other fruits and vegetables, showing a certain diversity within their farm. Only 33% of the greenhouse producers are growing other crops, which shows on the other hand the high reliance for tomato as a high value crop. However, the producers surveyed present also major differences in terms of accessibility to markets. While the open-field producers in RSK region only have access to local and regional markets, the greenhouse producers in SM region have both access to export market and local and regional markets.

3.4. Modeling framework

For explanatory purposes, the model is split into modules that explores the socio-ecological dynamics in the system versus the natural resources supporting it. We present here the main modules in order to explain the underlying links in each of the model outcomes that were chosen as sustainable indicators for this study.

3.4.1. Socio-economic modules

The following two sub-modules aim to represent the dual agricultural production system for tomato production in the country. A typology of two different modes of production and producers have been established in order to describe the situation in the two different regions of the country.

3.4.1.1. Open-field farmers dynamics. The farm management sub-module is a central part of the model, establishing the link between the social-ecological structures, namely the crop production and the income generation. This sub-module describes an open-field farm, producing mostly vegetables as a main source of income (incl. 'Net revenue from tomato production' and 'Other revenues'). Results from the survey indicates that open-field farmers are producing other crops, the seasonality of tomato production would enable themThe characteristics of the farm management have been designed according to the field observations and the average data from the survey (see Table 2). It is assumed here that those tomato producers are family farmers and have alternative sources of income (different crop production and/or off-farm activities). Open-field farmers in this specific context only have access to the local and regional markets. The main stock represents the farmers cash flow. It depends on the net income from tomato production and sales, other crop production and other activities (see R1 in Fig. 3). As the cash flow increase, farmers can increase their expenditures on machineries or irrigation systems, like digging their wells deeper regularly, which has a balancing effect of increasing the expenses and decreasing the potential cash flow (see B4 in Fig. 3).

3.4.1.2. Greenhouse producers' dynamics. Greenhouse production for export requires knowledge in terms of technical expertise, but also a different set of infrastructure and thus production costs (Aloui and Kenny, 2005; Sippel, 2016). With an initial capital to start the producing activities, exporters can invest in quality inputs, labor, and mechanized tools to produce a higher yield than open-field producers. Here again, three stocks characterize the economic dimension within the farm. The farm infrastructure is considered as a stock and is the one enabling producers to invest in the first place on mechanized tools, good quality inputs and land to extend their production area. Exporters' tomatoes have to meet certain standards of quality to be able to be exported to European and international markets – that explains the high costs of production (see Fig. 4).

3.4.2. Agricultural and ecological resource modules

3.4.2.1. Water and groundwater dynamics. This sub-module focuses on water management and groundwater use. The aquifers of the studied region are represented as stocks. Inflows to the stock come from upward drainage from deep aquifer, river and flood water infiltration, percolated water from irrigation and recharge from rainfall (ABHBC, 2012; Malki et al., 2017). The outflows are water discharges mainly driven by agricultural water consumption. Indeed, in both of the studied region, the use of the aquifers is mostly dedicated to irrigation and agricultural production. The more water is available in the natural reservoirs, the more water is accessible for agriculture and the easier it is to access it, but the more water is used for agriculture the less water is left in the natural reservoirs (see loop B9 in Fig. 5). Similarly, this reinforcing feedback loop occurs for the open-field farming region. The more water is available and use the higher is the intake for the crop (see R5 in Fig. 5). Higher water uptake leads to higher yields than otherwise, which eventually contribute to an increase in the household's revenue. Cash availability can result in irrigation infrastructure expenditure, as shown in Fig. 4, loop B5. The water consumed by the agricultural sector is a minimum function of the maximum water extracted for agricultural purposes and groundwater used for irrigation.

3.4.2.2. Yield. Finally, another core part of the model represents the interactions between input use and yields. The yields for both greenhouse and open field production are dependent on the effect of both water and fertilizer use. This agricultural sub-module has been elaborated to capture the influence of nutrient and water dynamics on yields (Gerber, 2016). The main reinforcing feedback loop R7 (see Fig. 6) describe the links between agricultural productivity, revenues generated by the production and expenses and use of fertilizers and water to increase the production. The nutrient uptake is influenced by the fertilization application and soil organic nutrient dynamics. The soil sub-module captures the main dynamics of the soil organic nitrogen and carbon in the soil. Soil organic carbon and nitrogen are two stocks linking fertilizers use and the soil dynamics. Nitrogen plant uptake affects directly the yields and constitutes a natural constraint of how much can be produced (R9). For further information see the appendix.

3.4.3. Modeling timeframe and simulations

To simulate the effects, we ran the model within a timeframe 2008–2050. On the one hand, the model covers the historical behavior of the last decade since the implementation of the GMP in 2008. On the other hand, the model is used to simulate the behavior until the year of 2050. The selected timeframe allowed 1) to validate the model by comparing its results to the actual data (see MethodX) and 2) to observe and understand the long-term environmental and socio-economic processes in this dual tomato production system. The first objective of the

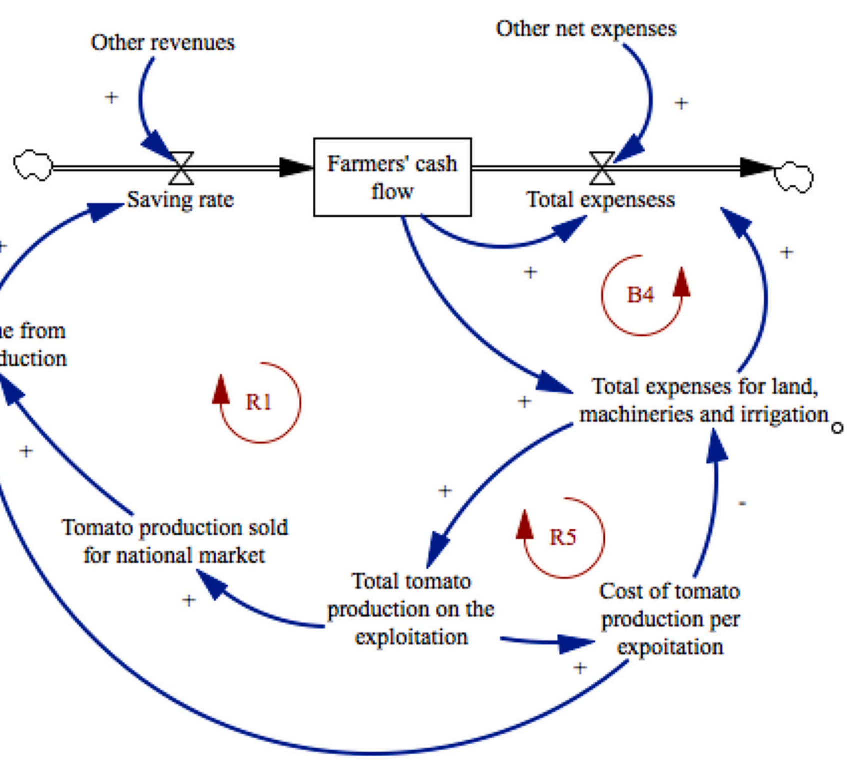

Fig. 3. Summarized state and flow model and the causal links of an open-field farm.

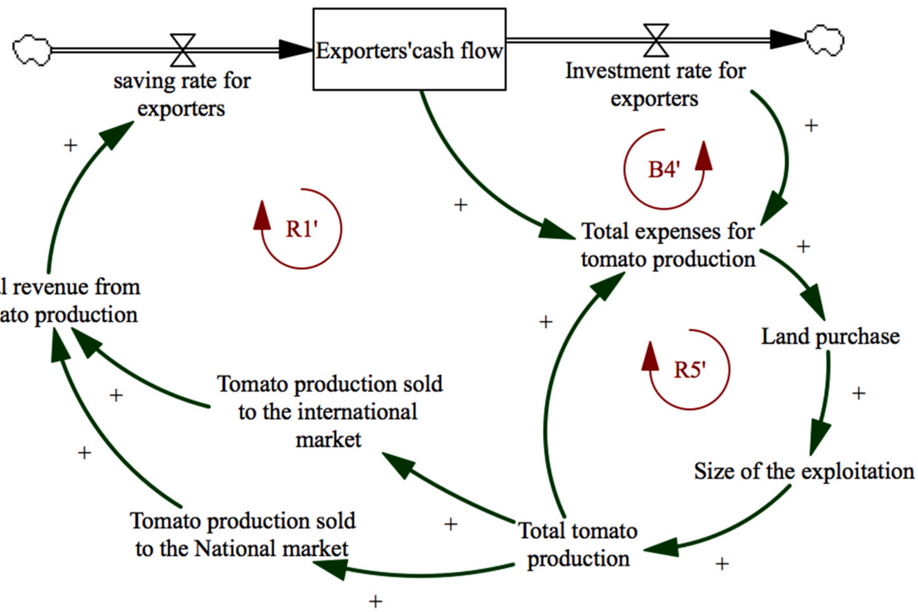

Fig. 4. Summarized state and flow model and the causal links of a greenhouse producer.

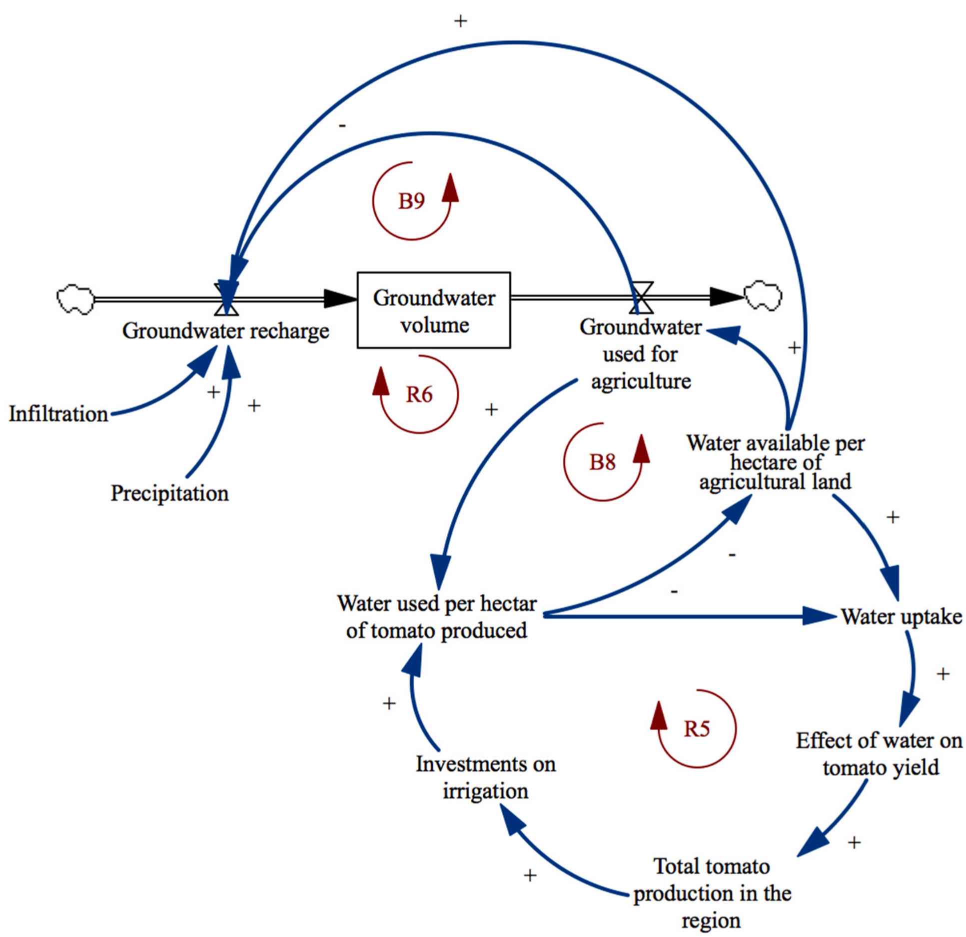

Fig. 5. Summarized state and flow model and the causal links for water and groundwater management dynamics.

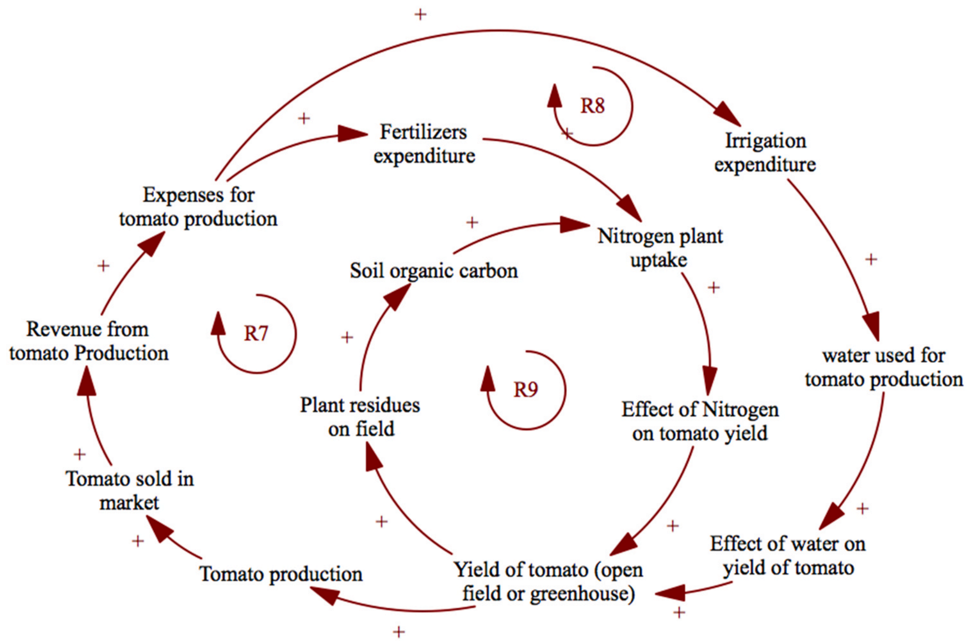

Fig. 6. Summarized causal links for yield dynamics.

simulation is to understand what major changes occur in the system. Then, we explore the cascading impacts of the changes on sustainability of these two agricultural systems through a sensitivity analysis. Two types of sustainability outcomes are displayed: groundwater availability of both aquifers and the producer's cash flow for open-field and greenhouse farmers.

4. Results and discussion

4.1. Modeling outcomes

In this section, we use the socio-ecological model to describe how current trends for water use and groundwater depletion affect tomato production, as well as socio-economic aspects.

4.1.1. Ecological domain – Groundwater

The aquifers dynamics highlight the severity of groundwater overexploitation in both regions (see Fig. 7). In both cases, we observe that the reinforcing feedback loops contributing to groundwater use, operate faster than the balancing one responsible for groundwater table recharge. The groundwater volume balance is not reached, leading to a quick depletion process, explained by the reinforcing loop R5 that is not balanced by the balancing loop B9 in Fig. 5. This acceleration is mostly explained by the conversion to drip irrigation and the expansion of intensive farming, especially for cash crop production like tomato, having thus an impact on water resources. As a result, the GMP plan to

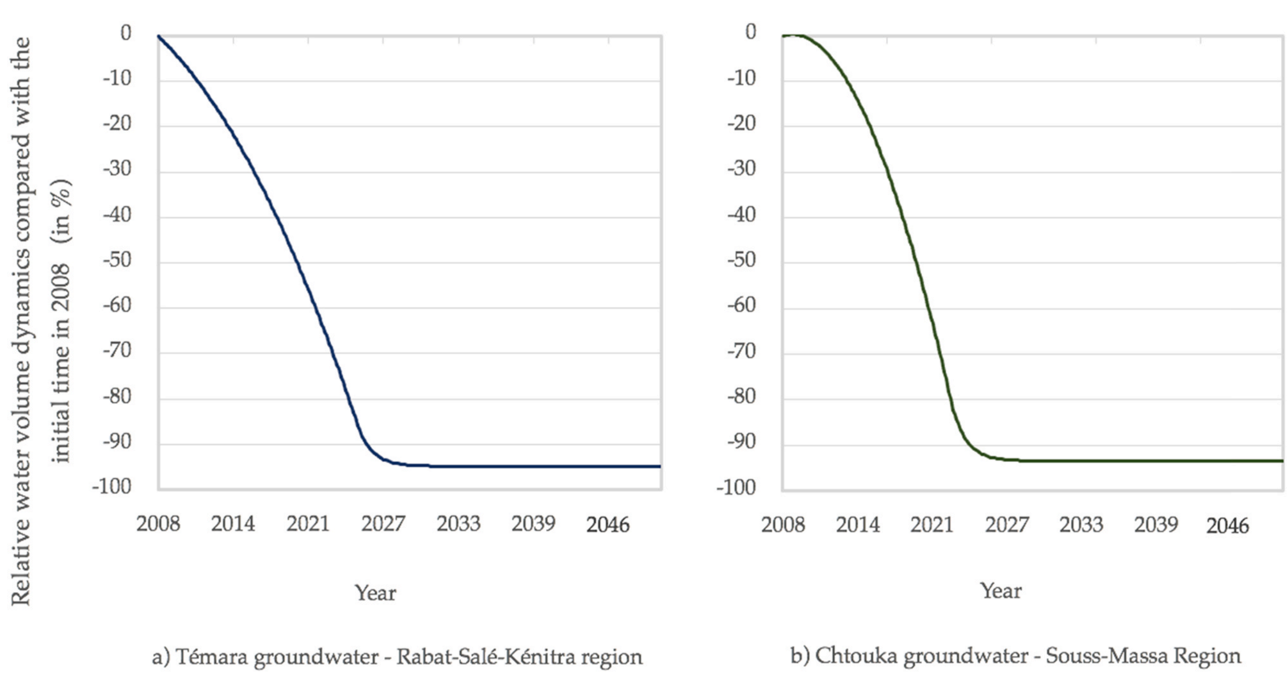

Fig. 7. Temara and Chtouka groundwater dynamics. Relative water volume dynamics compared with the initial time in 2008.

manage sustainably water resources appears to have failed in its initial intentions by having considerably promoted this irrigation practice (Molle and Tanouti, 2017b). This confirms the concerns regarding a decreasing water balance (Iglesias et al., 2007; Malki et al., 2017; Seif-Ennasr et al., 2016). Recharge of the groundwater tables is mostly driven by precipitation and infiltration (from irrigation or other water sources like rivers). However, a water balance can only be achieved in an aquifer through sustainable water management, where the volume extracted should be assigned according to the water recharge.

These graphs inform us on the transition from a regime relying on groundwater table to a regime where this irrigation option could not be available anymore. On the other hand, even though the same behavior can be observed in both aquifers, we found only literature reporting on the Chtouka groundwater volume (Ait Brahim et al., 2017; Hirich, 2016; Malki et al., 2017; Walters et al., 2018). The RSK region and more particularly the Temara groundwater volume has received only little attention in the scientific literature (Zouahri et al., 2014a). This raises a concern for the open-field producers of the RSK region. Ultimately, our observations regarding future water regimes are alarming for all the systems relying on groundwater-based irrigation.

4.1.2. Socio-economic domain– Producer's cash flow

The two different agricultural systems present two different patterns in the face of the same water depletion trend. For the open field tomato farmers, cash flow increases until 2019 (see Fig. 8). It appears that for today's farmers the benefits from tomato production has resulted from intensive irrigation and production leading to higher incomes (Molle and Tanouti, 2017b). Yet, a tipping point is projected to be reached in the coming years, leading the cash flow to continuously decrease until reaching back its initial value in 2030. The results show how the investment in irrigation for tomato production cannot cope with the effects of water depletion. For both types of producers, the balancing loops, enacting on irrigation systems, (see B4 and B4′, Fig. 3 and Fig. 4) appears to be faster than the two reinforcing loops sustaining production and investment for the cash crop (see R1,R1′,R5 and R5′, Fig. 3 and Fig. 4). Ultimately, the expenses for the production of tomato are not compensated by the prices and profits start to decrease. This tipping point is reached a few years before the groundwater decreases to more than 90% of its initial volume, the tomato national supply is then higher than the demand and the crop price tends to decrease. However, the overconsumption of water continues and start to have a direct effect on the production (see Fig. 8) and the yields start to decrease rapidly. For the exporter, a similar increase of their cash flow over the first 15 years is observed and is directly followed by a drastic decrease over a longer time period. However, an increase in exporters' cash flow is projected after 2030; it is explained by the link between tomato production yield and the profit. Namely, the yield starts to increase again due to the use of fertilizer and its effect on the crop. While water availability decreases, producers are still using adequate nutrients for the plant.

At the same time, it is observed that the scales for the evolution of the relative cash flow are not the same for each type of producer. While exporters are selling to both international and national markets, their profit remains higher than the local farmers, and despite the groundwater depletion, their cash flow could reach 6 times the initial one (see Fig. 8). These results reveal a significant difference between farmers involved in the groundwater economy and goes in line with what has been observed in other regions of the country (Ameur et al., 2017). The results also highlight an increasing gap between the two typologies of farmers. This appears as a second argument showing the failure of the strategy of the GMP aiming to uphold domestic agriculture and supporting the most vulnerable farmers. A threshold in producers' cash flow is reached and the subsequent tipping point indicates the necessity to change the regime in order to enable sustainable outcomes for all producers. The cascading effects of water overexploitation on yield and cash flow appears in this model to have long-lasting consequences for the producers.

4.2. Sensitivity analysis

In order to have a deeper understanding of the effects of key variables on the system, we conducted a series of sensitivity analyses. The results of the sensitivity analysis show that for farmers and exporters 'cash flow at the years 2030 and 2050 are shown in Fig. 9. The selected 10 exogenous variables of the model were tested under + 10 and − 10% difference from the baseline scenario, depicted in Fig. 7 and Fig. 8.

The sensitivity analysis, shows a minimal effect of a few indicators,

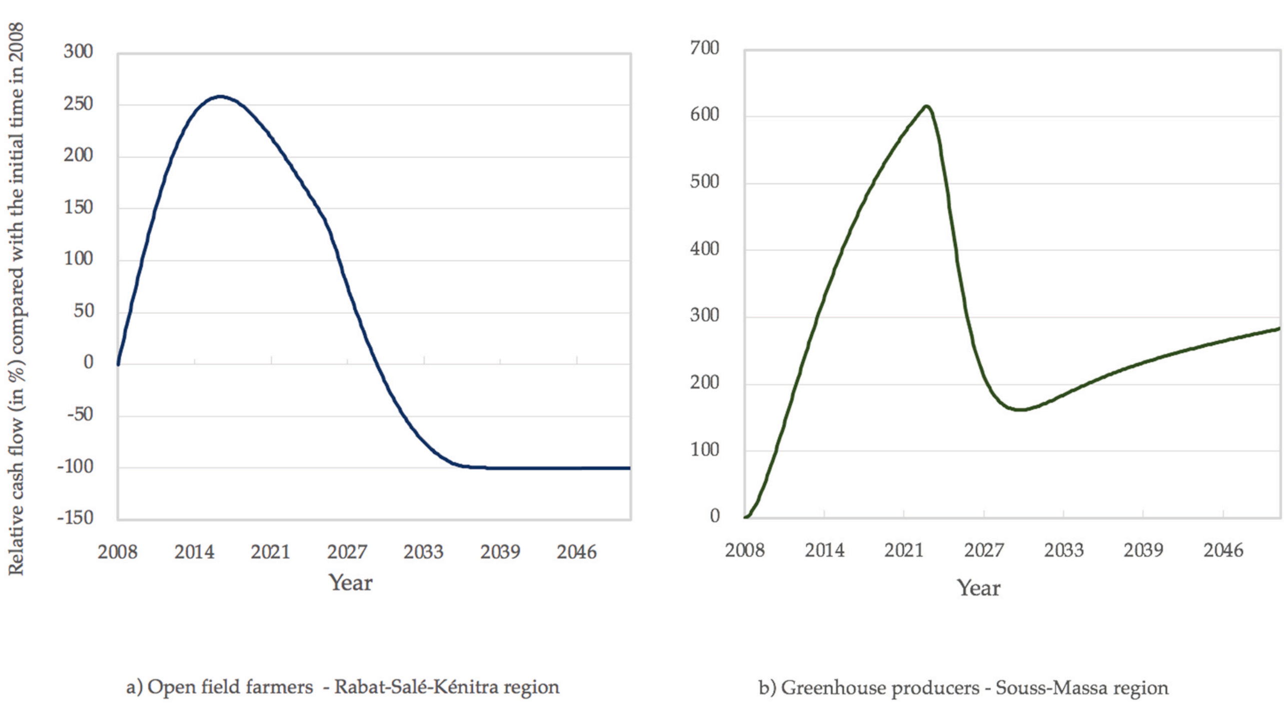

Fig. 8. Open field farmers and greenhouse producers cashflow dynamics. Relative cash flow in % compared with the initial time in 2008.

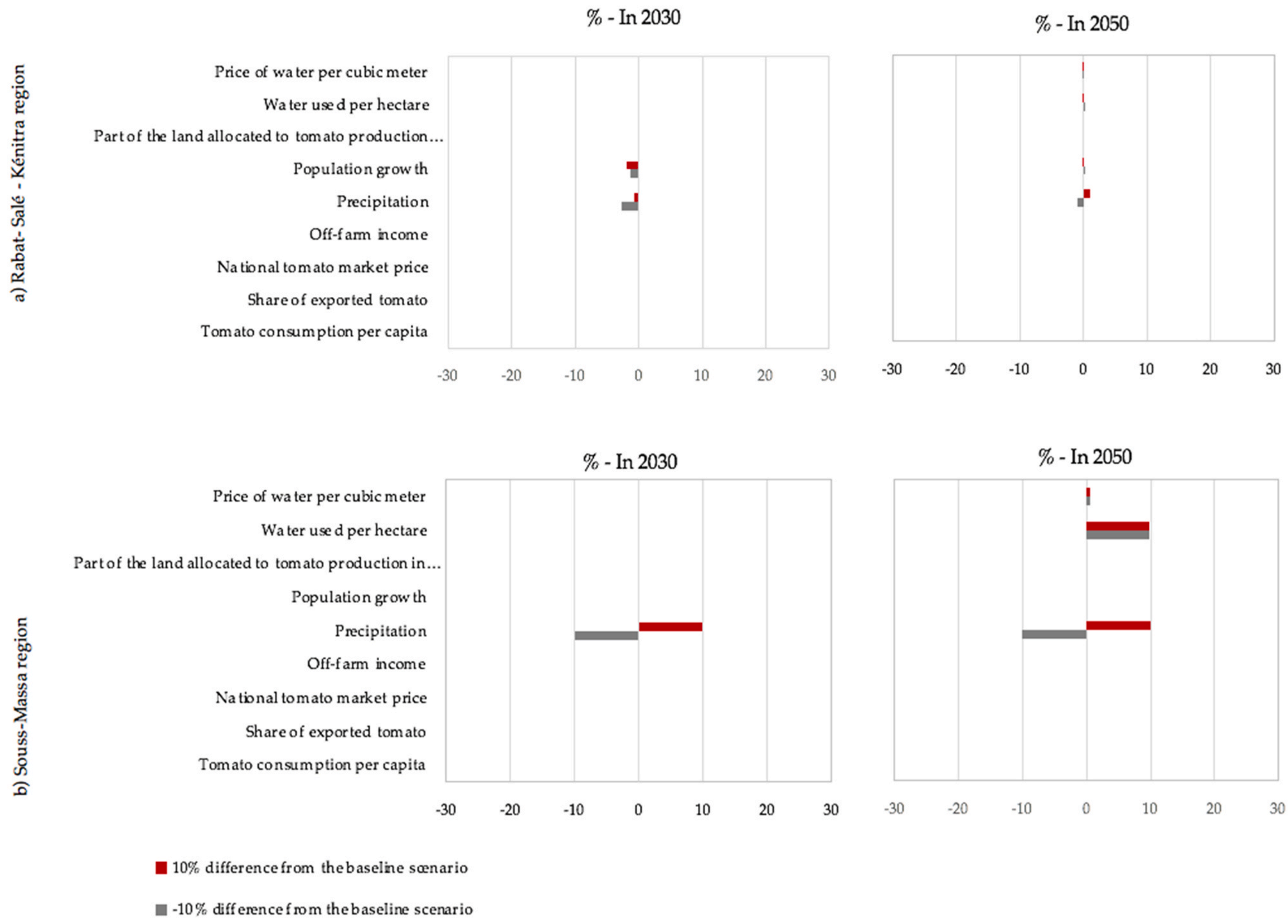

Fig. 9. Sensitivity analysis for a) SM groundwater volume and b) RSK groundwater volume.

such as water used per hectare and precipitation, on the groundwater table. None of the variation of the 10 indicators appear to have a significant effect on the groundwater table. In fact, in 2030 and 2050, groundwater volume would have already reached its minimal volume (see Fig. 9). The variation from − 10–10% of the sensitivity analysis, shows the incapacity at that stage to have a significant effect on the groundwater depletion trend. It points at the need for bigger endogenous changes or exogenous ones, such as alternative water supply for farmers. Furthermore, climate projections suggest that drought events will be more frequent in the future (Esper et al., 2007; Kusunose and Lybbert, 2014). This raises more concerns on groundwater recharge, that is mostly driven by precipitation. Frequent droughts could accelerate water depletion over the coming years. To a certain extent, these results show how critical the situation is for water resource management and that the variations of only one indicator is not enough to make a change. Thus, our results highlight that actions need to be taken in the coming years in order to prevent the irremediable situation of 2030.

Moreover, the observations from the sensitivity analysis for exporter cash flow (see Fig. 10) show that only an increase in the share of exported tomato and the total tomato consumption per capita could have a positive influence on their cash flow. It also appears that positive variations in terms of water supply has negative impacts on the cash flow of the exporters in the long-term. This is explained by the reinforcing feedback loop of groundwater management (see Fig. 5- R5); the more water is available, the more water is used, accelerating the process of depletion leading to water shortages before 2030. This has subsequent effects on the yield and thus on the profits from tomato sales. This translates the heavy dependence on tomato production of exporters, that mostly produce this cash crop and almost solely rely on its profits.

T7/20/2021 9:47:00 AMhe sensitivity tests show a more striking variability for farmer than exporter cash flow. In 2030, a raise in tomato market price appears to be one of the best fitted solutions for a cash flow increase. This variable raises the role of market structure and its effects on producer cash flow that rely heavily on this cash crop. Complementary information from the survey (see Table 2) shows that exporters are mostly linked to both markets. Moreover, farmer cash flow changes are considerable in 2050. We can observe a high variability for each variable, (e.g. water used per hectare, part of the land allocated to tomato production, tomato consumption per captia, etc.) which is explained by the outcome of the baseline scenario. Farmer cash flow in 2050 is estimated at 9 MAD (= 0.9 USD, see Fig. 10), thus, any variation is having a substantial effect on the relative outcome. Results from the sensitivity analysis shows the advantages of being linked to both markets in terms of cash flow generation. On the other hand, up to 21.1% of the farmers in RSK region have a seasonal alternative source of income, while only 1.2% in the SM region (see Table 2). This also comes to confirm the vulnerability of open-field farmers in face of market price variation.

Results from the sensitivity analysis shows that in order to reach sustainable outcomes for both producer cash flow and groundwater volume, there is a necessity to urgently enact on water resource management as well as to combine a set of policies that would effectively support open-field farmers toward a long-term prosperity, while decreasing the considerable gap between the two type of producers.

4.3. Synthesis and further research opportunities

4.3.1. Unsustainable and unequal spillovers

The model has shown that the agricultural strategy aiming for an intensification of the production driven by an increase access and use of groundwater has reached a critical limit. A tipping point was projected

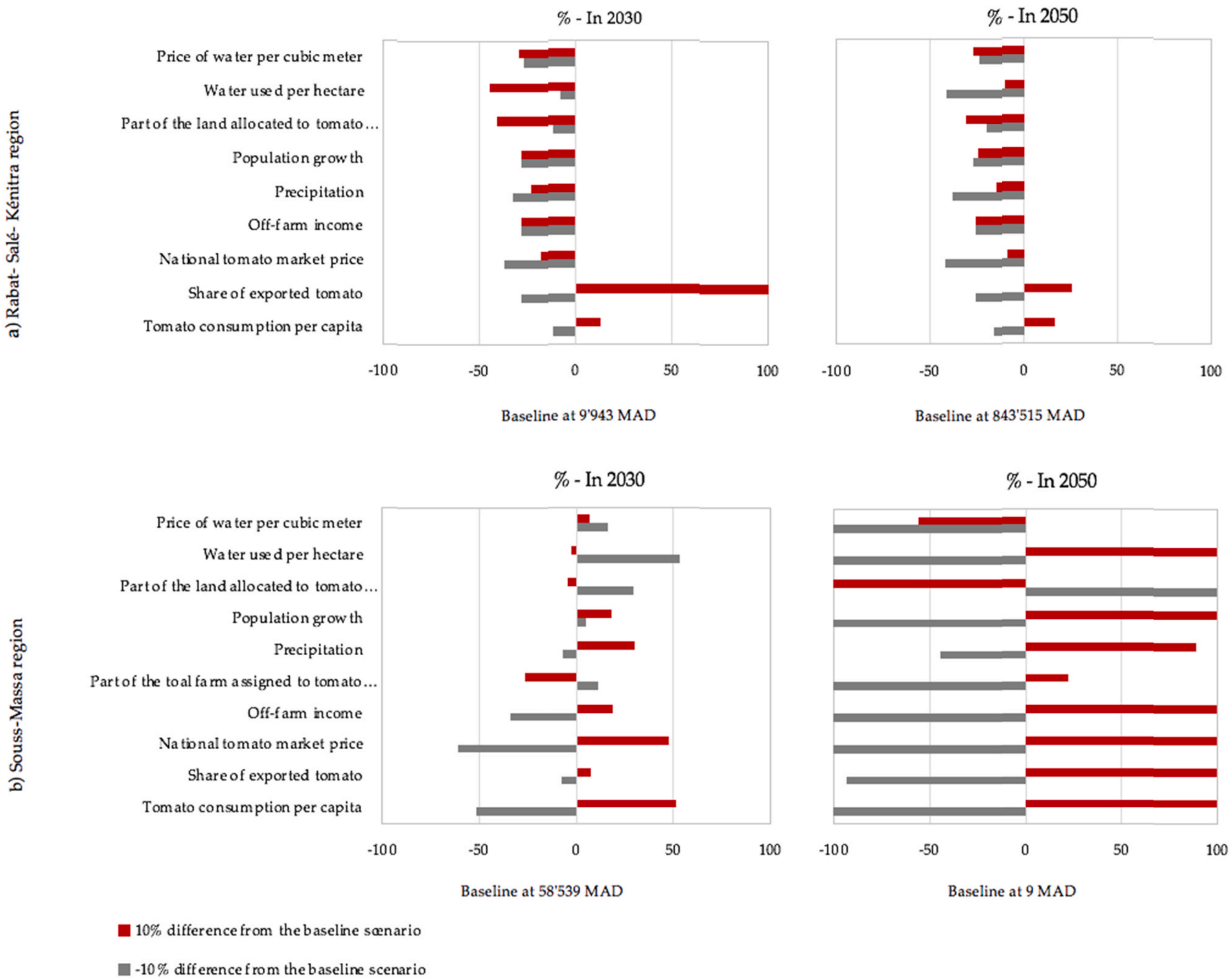

Fig. 10. Sensitivity analysis for a) exporter cash flow and b) Farmer cash flow in MAD (Moroccan Dirhams).

to be reached in the coming years between 2018 and 2023, and another reorganization of the farming and agricultural systems is needed to prevent a collapse for some farmers. This shift in the regime arises not only from gradual changes in a single variable, but from the interactions (e.g. between water access, land use and market access) among processes (e.g. production and trading) operating at different spatial and temporal scales (Filatova et al., 2016). When addressing the sustainable outcome of this system, temporality and reversibility become two major components to address. The temporality of the simulation shows how the major changes (i.e. scarce water availability and cash flow) operate within a 40 years' timeframe. A long-term overview of the system becomes crucial to anticipate irreversible change. When it comes to aquifer management, studies have shown the difficulty or sometimes the impossibility to recharge and restore the aquifers. Reversibility is often viewed with respect to the ecological system – whether a previous, typically more 'natural', regime can be restored – rather than the social-ecological system (Filatova et al., 2016). However, if we focus on the socio-economic sub-system, maintaining the agricultural activity becomes possible by supplying water from other sources than the groundwater or by implementing more water management practices. To this end, measures have been taken in the SM region to put in place a decree safeguarding the Chtouka aquifer and establish an irrigation perimeter from desalinated water (ORMVASM, 2018). The desalinization plant should provide water to the producers of the region in the coming years. However, no policy or longer-term plan have been announced for the RSK region, leaving high concerns for the fate of the most vulnerable farmers.

4.3.2. *Salinity incursions*

An extension of the model integrating the impacts of agrochemical impacts and saline intrusion on water quality and its effects on the yields and the cash flow over a longer time period could enrich the analysis. Several studies have reported nitrate pollution issues on water quality in both aquifers studied and the effects it could generate for producers (Malki et al., 2017; Zouahri et al., 2014b). The risks of saline water intrusion are such that already some farmers surveyed in the RSK region mentioned this issue. Not only vegetable production will be affected, but every type of irrigated crop would bare the irreversible consequences of sea-water intrusion. Existing models of salinization on irrigated land reveal that depending on the drainage, the groundwater discharge and the groundwater intrusion the salinity reaches alarming levels and with what strategies it can be controlled. As an example, a common strategy of increasing the drainage in order to control the salinity level yields to growing salinity levels, and have a catastrophic result for crop production and agriculture in general (Saysel and Barlas, 2001). For the purposes of our project, this was not modeled, due to the lack of reliable information and sparse data. However, the model has been shaped in order to be able to add sub-modules related to those issues.

4.3.3. *Regime shifts and climate resilience*

Climate change and droughts affecting the country represent also major concerns that have the potential to speed up the process of groundwater depletion (Ezzine et al., 2014; Kusunose and Lybbert, 2014; Ouatiki et al., 2019). Empirical studies on ecosystems have shown that slowly changing conditions can cause quite abrupt changes in the functioning of a system (i.e., regime shifts; Scheffer and Carpenter, 2003). For example, soil salinization has been reported as an example of regime shift happening in socio-ecological systems, especially impacting water tables and agricultural production systems (Anderies et al., 2006; Biggs et al., 2018) Under constant changes in environmental, ecological, political, and socioeconomic conditions, the likelihood of regime shifts increase and reduce human resilience. The combination of various pressures, such as coupled water depletion and climate change could make the ecosystems even more vulnerable to changes that could have been absorbed (Folke et al., 2004; Walker et al., 2004). In this study, groundwater depletion leads to a new state that is driven by endogenous gradual change, and allows us to project a potential regime-shift. A regime shift suggests a loss of resilience, in that former functions, structures, feedbacks of the systems (Cumming and Collier, 2005; Kinzig et al., 2006). A combined threat of increasing droughts and a foreseen groundwater depletion questions the resilience of the tomato production system. Minimizing trade-offs and optimizing the sustainability of such system can be a challenging task that requires further analysis of SDM and integrated policy support.

5. Conclusion

We have brought a different perspective on the agricultural situation in two Moroccan localities (Chtouka and Temara) representing two of the main agricultural regions of the country (Souss-Massa and Rabat-Salé-Kénitra). On the one hand, this study raises more than ever the awareness about the dynamics of using groundwater in both regions and the consequences of its over-exploitation on producers of both regions. On the other hand, it also enables to draw an alarming conclusion on the implications of the green Morocco plan, as a strategy aiming to uphold smallholder farmers as well as promoting high added value crop production for export. This strategy has failed some rural population by enhancing the socio-economic gaps, and increasing vulnerability to a vital resource, water. Through the use of SD modelling, this study allowed to gather information from stakeholders and literature and captures a more holistic vision of this complex agricultural-system. Multiple methods, both quantitative and qualitative, allowed to elucidate the effects of the irrigation schemes on the global and local tomato producers. The main purpose of this study was to show a) how global and local tomato value chains respond to irrigation schemes and b) what the environmental consequences are. To this extend, our study confirms other findings in that the boom in the groundwater economy benefitted entrepreneurial and well-endowed farmers, oriented towards the global tomato value chain market, who made intensive use of groundwater. While the effects of the over-exploitation of groundwater fed the marginalization of family farmers supplying local tomato value chains, we also conclude that there is an urgent need to resolve access to and use of groundwater in the face of declining water tables, as the current environmental consequences of the policies in place are alarming. Socio-economic inequalities between exporters and open-field farmers remain unaddressed. The bond, aimed by the GMP between this dual production system, has not proven to be build or efficient. Ultimately, this interdisciplinary study addresses agricultural water management in a systemic, as well as a systematic, manner. Such approach, has been the first one used in the Moroccan context and aims to pave the way for further systemic socio-ecological studies.

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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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Conflicts of Interest

The authors declare no conflict of interest. The funding research council had no role in the design of the study, in the collection, analyses, or interpretation of data, in writing the manuscript, or in the decision to publish the results.

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