MAIN ARTICLE

# Managing the trade-off between groundwater resources and large-scale agriculture: the case of pistachio production in Iran

Ali Akhavan* and Paulo Gonçalves

*Abstract*

Benefiting from historically favorable conditions (e.g. low costs, fertile land, and abundant water), pistachio producers in Rafsanjan, Iran, have flourished, with pistachio orchards and production growing dramatically since the 1970s. Today, however, the enormous increase in water consumption associated with pistachio production has severely depleted groundwater aquifers, causing widespread water shortages in the region. In this article, we develop a comprehensive system dynamics model, combining the agronomic, economic, hydrologic, and behavioral aspects to analyze the long-term implications of pistachio production. Our research contributes to the literature of agricultural water management in three significant ways: (i) it provides a validated and quantitative model exploring pistachio farming for a region; (ii) it explicitly captures behavioral decision rules associated with orchard growth and production investment; and (iii) it addresses a natural common-pool-resources problem with very long-time horizons. We consider several policies aimed at addressing the problem (e.g. water transfers, drip irrigation, financial subsidies, income tax, water pricing, and land purchasing). Our results suggest that policies that increase the effectiveness and efficiency of production (e.g. water transfer and drip irrigation respectively), albeit preferred by farmers, lead to better-before-worse results, depleting groundwater storage in the long term. Insights from the model can help policymakers have a better understanding of the unintended consequences of their policies.


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## Introduction

Rafsanjan, a semiarid region located in central Iran, has long been recognized for its massive high-quality pistachio production. By generating near $ 1 billion annually, Rafsanjan has had a significant impact on the regional economy. More than 30,000 people are directly involved in the production by owning or managing pistachio orchards (FAO, 2019; Iranian Pistachio Association, 2019). Rafsanjan has accounted for most of Iran's pistachio production and contributed more than 20 percent to global supply during the

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1980s and 1990s (Ferguson and Haviland, 2016). Along with the favorable climatic conditions, the Iranian government has provided energy and water subsidies over the past several decades, making the area as attractive as possible for potential producers (Madani, 2014).

Despite its considerable benefits to the state economy, pistachio production in Rafsanjan consumes enormous amounts of water, which cannot be easily found in the region. Indeed, economically viable pistachio production requires specific climatic conditions, including long, hot summers and sufficient chill in winters (Benmoussa *et al*., 2017; Elloumi *et al*., 2013). These favorable conditions occur in areas far from surface water resources such as rivers or lakes. Thus, pistachio producers in Rafsanjan have long relied on groundwater as the only source of water for irrigation (Mehryar *et al*., 2016; Motagh *et al*., 2008).

Over the past decades, due to the high profitability of pistachio production, orchard area has increased significantly, resulting in overextraction of groundwater as well as a serious decline in the water table (Mehryar *et al*., 2016; Mehryar *et al*., 2019). The groundwater decline has increased the cost of water pumping, reduced the quality of water, and has resulted in significant land subsidence, which is detrimental to both the regional economy and the environment. The average depth of water well in the 1970s was about 20 m, while today reaches to more than 300 m (Iran Water Management Institute, 2014; Motagh *et al*., 2017).

To manage and improve groundwater, scholars have investigated and proposed several direct and indirect measures, including permit and licensing systems (Chebaane *et al*., 2004; Shah *et al*., 2003) and incentives for irrigation efficiency (Dench and Morgan, 2020). While these solutions appear reasonable, they often are ineffective or lead to counterintuitive outcomes. For instance, although the Ministry of Water and Irrigation in Jordan banned water-well drilling in the 1990s by introducing licenses, the continuous water extraction from the already established wells resulted in more groundwater consumption (Chebaane *et al*., 2004). In a recent study, researchers found that improved irrigation efficiency to mitigate the shortage of freshwater in New Zealand has caused an increase in overall water consumption and further declined the groundwater level (Dench and Morgan, 2020). These examples show that myopic policies looking at one part of the problem can cause unintended consequences over time.

To address this issue, we develop a comprehensive system dynamics model, combining the agricultural, economic, hydrological, and behavioral perspectives of the system to analyze the long-term implications of different government policies. The system dynamics model captures concepts from diverse literature streams including common pool resources (Gordon, 1954; Hardin, 1968), decision-making heuristics (Sterman, 1987, 1989), and theory of production in economics (Farrell, 1957). Finally, we have calibrated the formal model using 30 years of time-series data on several variables including: orchards, irrigation, pistachio production,


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pistachio prices, rain precipitation, and groundwater levels. This article contributes to the literature of agricultural water management in three significant ways (i) it provides a validated and quantitative model exploring pistachio farming for a region; (ii) it explicitly captures behavioral decision rules associated with orchard growth and production investment; and (iii) it addresses a natural common pool resources problem with very long-time horizons.

We focus on the policies that address economic growth by increasing water availability, enhancing efficiency, and financial incentives and policies that attend water resources conservation by regulating water price, financial disincentives, and controlling the cultivated lands. Through a system dynamics model based on the case of Rafsanjan, we show that combination of policies trying to support farmers while protecting the environment, although being helpful in the short term, would result in unintended adverse consequences in the long term.

Theoretically, pistachio production in Rafsanjan can be representative of other regions characterized by: (i) dependence on and competition for a scarce resource (e.g. groundwater), (ii) the common resource as the main input enabling economic activity (e.g. pistachio production), and (iii) decisions related to economic activity face long delays before consequences for resource use materialize (e.g. orchards development). Empirically, we have collected extensive time-series data spanning 30 years on (i) resource use (e.g. water consumption for irrigation), (ii) economic productivity decisions (e.g. planted orchard area, annual pistachio production, pistachio price), and (iii) the impact of economic productivity on the common pool resource (e.g. revenues, orchards development, active orchards, and their impact on groundwater levels). Thus, the case of Rafsanjan satisfies the conditions for empirical and theoretical generalization (Eisenhardt, 1989; Eisenhardt and Graebner, 2007). Fenhe Region in Shanxi Province, China (Zhang and Guo, 2016), and the High Plains region of the United States (Foster *et al.*, 2017) where farmers grow multiple crops, including maize and wheat, are among similar regions that could be studied from a similar perspective. This study points out the circumstances governing groundwater management in such regions, meaning that existing or proposed future policies fail to achieve sustainable growth.

In the next section, we describe the background and the trend of some key variables over time. Next, we discuss the extant literature on system dynamics models exploring groundwater management. The following section explains the information sources and the conceptual model focusing on agricultural activities and groundwater consumption. Next, we explore the model development process. We present a formal mathematical model followed by a detailed calibration procedure. Finally, we report the implications of different policies on agricultural water management.


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## The case

For more than a century, Rafsanjan, located in a semiarid part of Iran, has been recognized for its massive high-quality pistachio production and has been among the top producers and exporters worldwide (Rafsanjan Municipality, 2014). The region has contributed more than 20 percent to the global pistachio supply during the 1980s and 1990s (Ferguson and Haviland, 2016). Iran's pistachio exports are worth more than $1.5 billion, a third of which is attributed to the Rafsanjan region (IRNA, 2019a), and after oil, the value of pistachio exports is the second largest in Iran.

To have the best growth and highest produce, pistachio trees require semiarid climate with long and hot summers and cold winters (Elloumi *et al*., 2013; Ferguson and Haviland, 2016). This favorable condition exists in Rafsanjan making the area highly attractive to potential farmers for at least 1000 years (Bloomberg, 2020). Around a century ago, farmers in Rafsanjan realized how to commercialize pistachio production, while the global market have become more accessible (Abtahi and Faizi, 2012), causing pistachio orchards expansion during the past several decades (Figure 1).

Currently, there are around 80,000 ha of pistachio orchards in Rafsanjan (IRNA, 2019b), whereas, in 2006, the cultivated area had reached more than 110,000 ha (Razavi, 2006). Almost all agricultural lands are dedicated to pistachio production, and more than 95 percent of water resources are used for irrigation (Mehryar *et al*., 2015, 2016). In recent years, production has declined because of water scarcity, and pistachio growers are leaving their orchards and reducing the cultivated lands (Figure 2).

Groundwater has been the primary source of water for irrigating pistachio orchards. Due to the government subsidies for supporting agricultural activities and overexpansion of orchards, water pumping has consistently exceeded

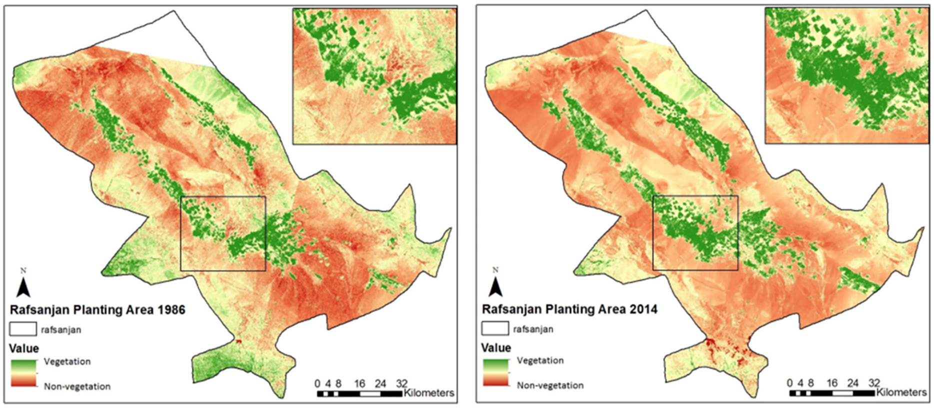


Fig. 1. Expansion of pistachio orchards in Rafsanjan 1986–2014. Source: (Mehryar *et al*., 2015) [Color figure can be viewed at wileyonlinelibrary.com]


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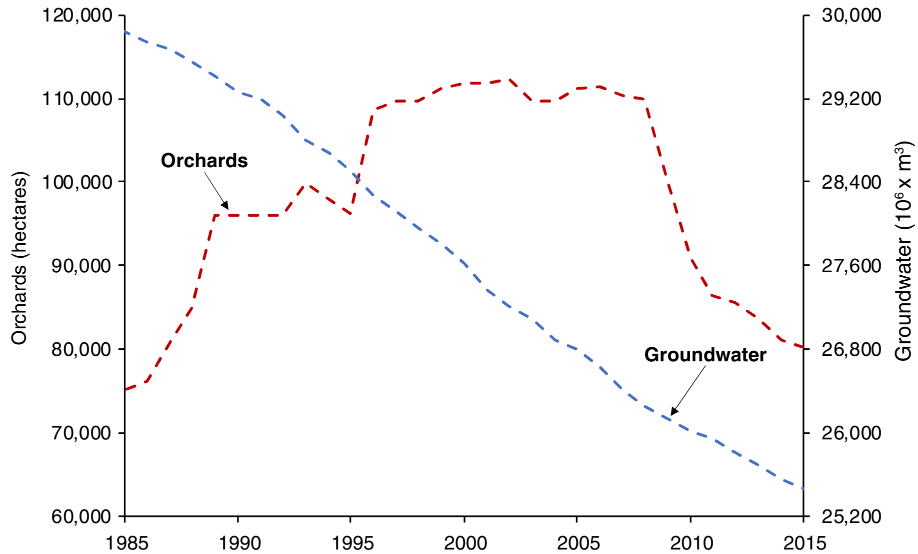


Fig. 2. Pistachio orchards area (hectares) and groundwater volume ($10^6 \times m^3$) in Rafsanjan 1985–2015. Source: (FAO, 2019; Iran Water Resources Management Company, 2016; Iranian Pistachio Association, 2019; Razavi, 2006; Torabi, 2016) [Color figure can be viewed at wileyonlinelibrary.com]

the groundwater inflow rate (Torabi, 2016). The number of water wells has increased from around 200 in the 1950s to more than 1300 in the 2010s (Figure 3). Although in the late 1960s more than 50 percent of wells were unregistered, the fraction dropped to less than 5 percent in the mid-2010s. These wells are owned and operated privately, and farmers do not pay for the water to the government. Instead, they incur the cost associated with pumping, irrigation, and other types of costs regarding water acquisition, such as informal water trading or small-scale water purchase and transfer.

The growing number of wells in addition to the continuous pumping have caused the average depth of the water table to increase from 20 m to more than 300 m during the past several decades (IRNA, 2017). Estimations show that the aquifer faces an approximately overextraction of 200 million cubic meters per year, causing land subsidence surpassing 20–30 cm per year (Motagh *et al.*, 2017). Moreover, the groundwater storage has reduced approximately 5000 million cubic meters during the past decades (Torabi, 2016).

Pistachio production has had a fluctuating pattern over the past decades. There are several reasons for this fluctuation. First, pistachio trees are alternate bearing, meaning that the yield is extremely higher once every 2 years (Ferguson and Haviland, 2016) Second, environmental factors such as temperature in summer and winter have also significant effects on the yield (Elloumi *et al.*, 2013; Lobell *et al.*, 2007). Finally, there is a heterogeneity in the yield among producers resulting in more variations in the production level (Ferguson and Haviland, 2016).


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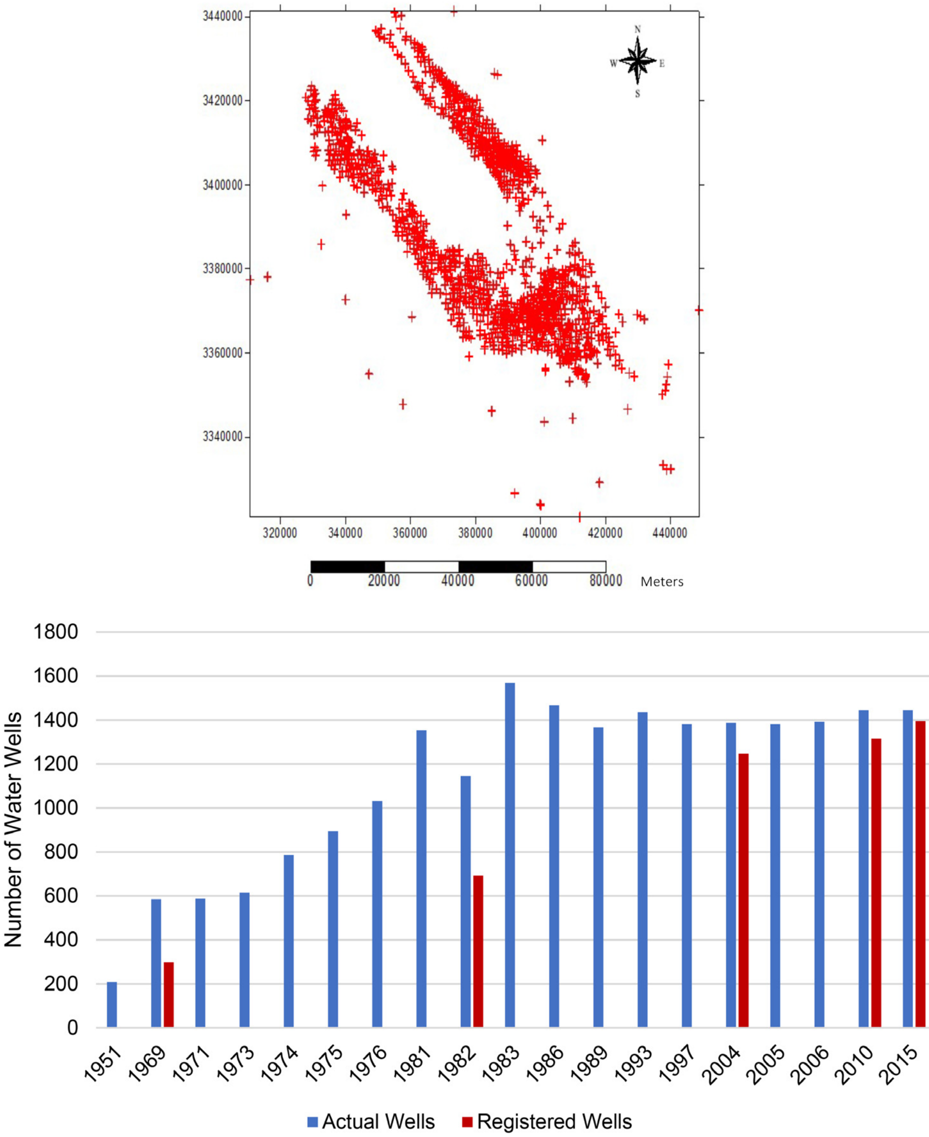


Fig. 3. Position of pumping wells in 2013 (on the left) and the evolution of actual vs. registered number of water wells (on the right) in Rafsanjan. Source: (Iran Water Management Institute, 2013; Rahnama and Zamzam, 2013; Zaraatkar and Golkar, 2018) [Color figure can be viewed at wileyonlinelibrary.com]

## Literature review

Researchers in water, groundwater hydrology, and agricultural water management have used system dynamics to analyze complex social-ecological systems. Fernández and Selma (2004) develop a model to capture the socio-economic and environmental factors that lead to overexploitation of aquifers


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and seawater intrusion in Mazarrón and Aguilas, Spain. Khan *et al*. (2009) represent a model of surface-groundwater interaction, capturing how aquifers react to changes in lateral flows, precipitation, percolation, and water extractions for the case of Yellow River Basin, China. Rehan *et al*. (2011) present a water-management model focusing on the demand side and the associated economic considerations for typical water utilities in Canada. Niazi *et al*. (2014) develop a model emphasizing on evaporative water losses and agricultural activities, showing means to preserve groundwater by reducing the evaporation and providing water for agriculture in Sirik, Iran. Balali and Viaggi (2015) represent a model of groundwater capturing the costs associated with pumping rate and how different pricing policies can influence the groundwater depletion in Hamadan Plain, Iran.

Although these papers offer a good understanding of groundwater dynamics, they have their own limitations by focusing only on parts of the system usually ignoring delays and nonlinearities in other environmental subsystems and behavioral complexities in economic dimensions. More importantly, they often lack rigorous model documentation, calibration, validation process, and quantitative analysis that undermine the usefulness of these models. Recent studies have tried to present more comprehensive system dynamics models for groundwater.

Jeong and Adamowski (2016) present a thorough model concentrating on groundwater hydrology, population, land use, and economic dimensions showing how different policies can affect groundwater use in the Osan River watershed in South Korea. Although the model is not available, authors provide the equations for each sector. They also calibrated and validate the model before policy analysis. A limitation of the model is the lack of a link from the groundwater to the water demand. In other words, the demand is determined exogenously from the population.

Li *et al*. (2018) demonstrate a model capturing population, economic, water supply, and water-demand subsystems to estimate the future water demand and to minimize the water-supply costs for Zhengzhou City, China. The model documentation and equations are partially available. Unfortunately, the authors only compare the simulation results with the historical data without explicitly reporting the calibration and validation process.

Finally, Barati *et al*. (2019) provide a general groundwater model including population, economic, and environmental subsystem to investigate the effectiveness of groundwater governance policies for sustainable use of this resource in Iran. The authors fully present model documentation, calibration, sensitivity analysis, and validation process. However, since the generalized model is developed at a country level, it is difficult to assess its usefulness in applying different economic instruments.

In summary, despite the mentioned shortcomings in the literature, research using system dynamics to study the groundwater have offered unique insights into our understanding of such complex systems. Our


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model, however, differs from the previous studies. First, we focus on a case where we can operationally model the interactions of agricultural, hydrological, and economic subsystems. Second, we carefully capture the delays and nonlinearities within each subsystem to better replicate the fundamental dynamics. Third, we explicitly represent a link from the groundwater resources to other sectors by endogenizing the economic variables such as profitability and water costs and how users of groundwater react to changes in these variables. Fourth, we report full model documentation, calibration, sensitivity analysis, and validation process. Finally, the proposed policy analyses reflect the actual government plans that if applied can have a variety of consequences for different stakeholders.

## Information sources and the conceptual model

To adequately manage groundwater reservoirs to sustain agricultural production requires understanding of specific concepts in different disciplines (e.g. economy, agriculture, water hydrology, etc.) as well as their interconnections and cross influences. Our system dynamics model captures the key feedback and nonlinear relationships connecting the economical, agricultural, and hydrological aspects of the model. In addition to the archival data, we conducted 25 semistructured interviews (in person and by phone, ranging between 30 to 90 minutes) and a few focus-group meetings. We interviewed different stakeholders including farm owners, farm managers, local authorities, and several experts in pistachio production and groundwater hydrology. The in-depth interviews were complementary and helped us better understand the relation between some of the variables in our model. Specifically, they informed us on farmers decision to grow/decrease orchards based on the profitability. We realized that farmers increase their orchards above a threshold in profitability, while they reduce the orchards below that threshold. They also revealed that farmers use flood irrigation, believing that they can increase yield by using more water. Hence, the implication for our model was a linear relation between the orchards' area and the water-pumping rate. The data gathered from the interviews and the existing literature provided the basis for our dynamic hypothesis (Figure 4).

Due to the perfect climatic conditions, government subsidies, and low costs, producers have profited from the pistachio production over the past years. High profitability attracts producers' attention to more cultivation. Higher rates of cultivation result in an increased level of orchards, which gives rise to the production, with a considerable delay (R1—Revenue Growth). Increase in orchards area raises labor and water consumption, contributing to production (R2 & R3—labor and water effects). Since cultivating young orchards requires vast investments and around more than 5 years is needed to reach the highest yield levels, the associated fixed costs prevent


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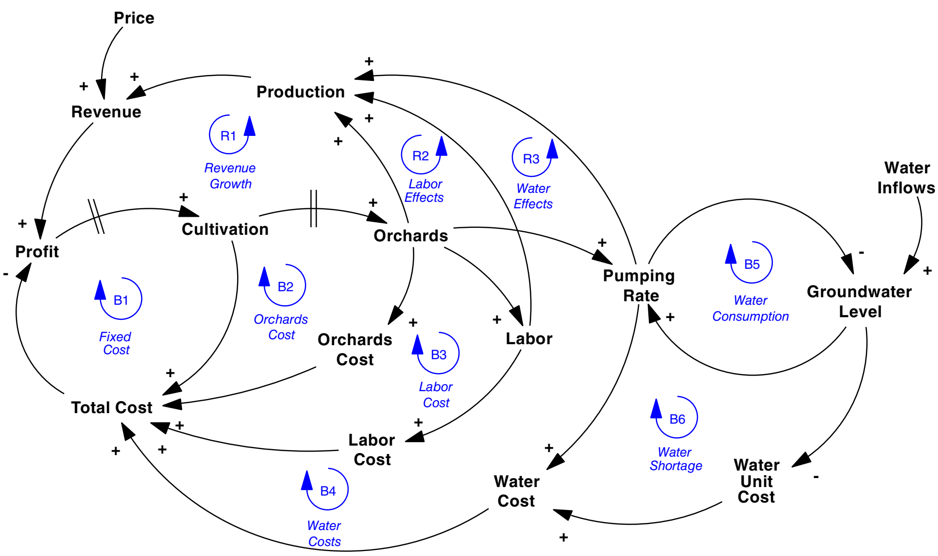


Fig. 4. Main feedback loops [Color figure can be viewed at wileyonlinelibrary.com]

the infinite revenue growth and balance the revenue–cost ratio (B1—Fixed Cost). Moreover, orchards maintenance and materials used for production (B2—Orchards Cost), labor compensation (B3—Labor Cost), and cost of acquiring water (B4—Water Cost) control the revenue growth.

To have an economically harvestable yield, producers must irrigate orchards frequently. More orchards increase the need for more water; therefore, pumping from the groundwater, as the primary source of water in the region, surges. Accordingly, if the pumping is higher than the inflow to the groundwater, which has been the case over the past decades, the groundwater level declines, resulting in less available water. Lower water availability reduces pistachio production (B5—Water Consumption).

Moreover, as the groundwater level decreases, the cost of acquiring water increases. This includes the cost of drilling, pumping, water-well maintenance, and so on, which hugely affects the profitability of farmers (B6—Water shortage).

Water inflow includes precipitation and later flows to the groundwater. Although excess water pumping may change soil properties and affect water infiltration in the long term, we treat this variable exogenous to the model. Pistachio price is also exogenous, determined in global markets.

## Model development

In this section, we present a formal mathematical model of pistachio production that combines groundwater, price, and profitability dynamics with


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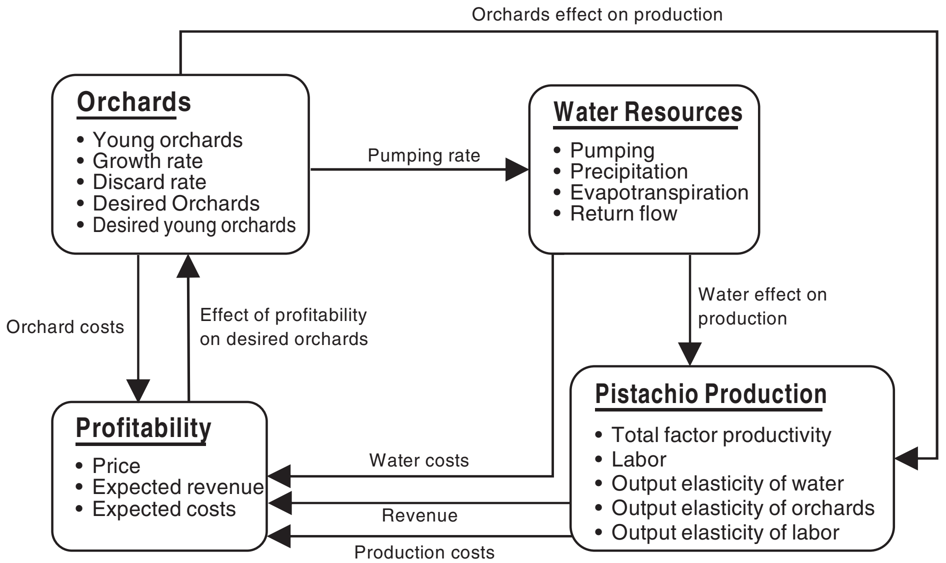


Fig. 5. Overview of the model structure

farmers' decisions to cultivate orchards. The integrated model allows us to evaluate the impact of pistachio production on groundwater depletion. Equations present theoretical foundations and evidence for hypothesized causal relationships.

Following the reporting guidelines for simulation-based research in social sciences (Rahmandad and Sterman, 2012), the model is fully documented, including explanations for the relations between observed variables, and is available in the online supporting information. Other researchers can critique, replicate, and extend this model to similar cases.

The model contains four sectors (Figure 5). The *orchards* sector tracks the flow of orchards from planting to bearing. Desired orchards and desired young orchards influence the planting rate. The *water resources* sector captures the balance of water flows from precipitation, evapotranspiration, returns, and pumping required to cultivate and irrigate orchards. The *pistachio production* sector details the relationship between orchards, water, labor, and production. Finally, the *profitability* sector captures the producers' reactions in response to various profitability levels, which influence the decision for cultivation.

### *Orchards*

The orchards sector tracks the aging chain structure of orchards (Figure 6), measured in terms of their area (hectares). Young orchards ($Y$) grow with Planting Rate ($PR$) and decrease with Growth Rate ($GR$). Orchards ($O$)


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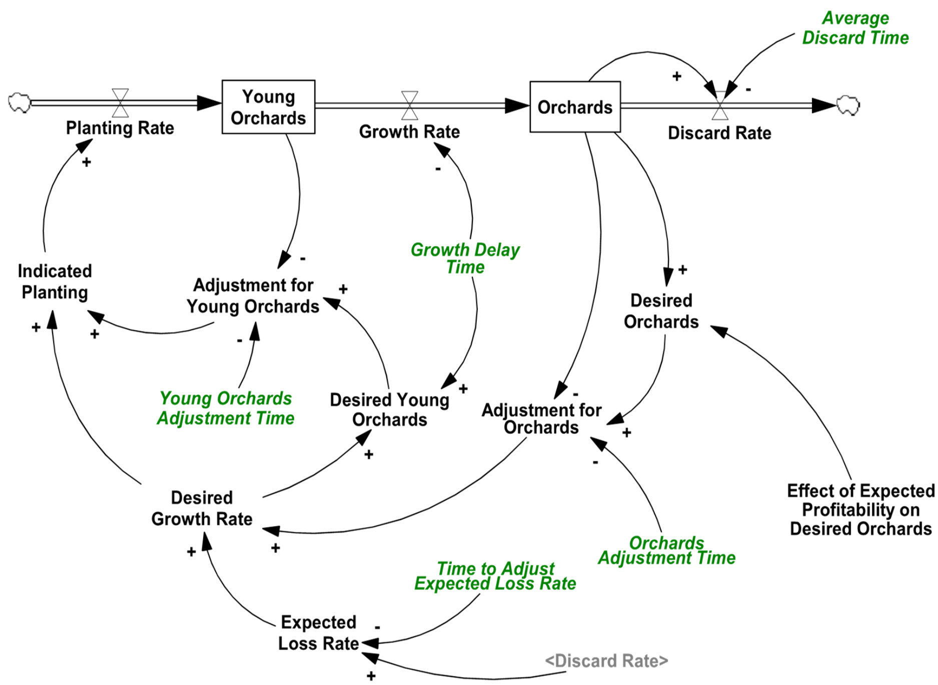


Fig. 6. Simplified stock and flow diagram for the orchards sector [Color figure can be viewed at wileyonlinelibrary.com]

accumulate the Growth Rate (*GR*) from young orchards and are reduced by the Discard rate (*DR*):

$$\frac{dY}{dt} = PR - GR, \tag{1}$$

$$\frac{dO}{dt} = GR - DR. \tag{2}$$

The Planting Rate (*PR*) is determined by the Discard Rate (*DR*), the Adjustment for Young orchards (*AY*), and the Adjustment for Orchards (*AO*). The Growth Rate (*GR*) is a third-order delay of Planting Rate (*PR*) with the Growth Delay Time ($\tau_{GD}$). The Discard Rate (*DR*) expresses the rate at which Orchards (*O*) are discarded. The rate also captures orchards losses due to natural causes. The Discard Rate (*DR*) is given by the Orchards (*O*) and the constant Average Discard Time ($\tau_{AD}$):

$$PR = Max(0, DR + AY + AO), \tag{3}$$

$$GR = DELAY3(PR, \tau_{GD}), \tag{4}$$


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$$DR = \frac{O}{\tau_{AD}}. \tag{5}$$

The Adjustment for Orchards ($AO$) and Adjustment for Young orchards ($AY$) reflect producers' considerations of the current level of orchards and young orchards when deciding for cultivation. The difference between the Desired Orchards ($O^*$) and the level of Orchards ($O$) divided by the constant Orchards Adjustment Time ($\tau_{OA}$), which is estimated via partial calibration, determines the Adjustment for Orchards ($AO$). Similarly, the gap between the Desired Young orchards ($Y^*$) and the level of Young orchards ($Y$) divided by the Young Orchards Adjustment Time ($\tau_{YA}$) determines the adjustment for Young Orchards ($AY$):

$$AO = \frac{O^* - O}{\tau_{OA}}, \tag{6}$$

$$AY = \frac{Y^* - Y}{\tau_{YA}}. \tag{7}$$

Substituting Eqs. (5)–(7), on Eq. (3) yields:

$$PR = Max\left(0, \frac{O}{\tau_{AD}} + \frac{O^* - O}{\tau_{OA}} + \frac{Y^* - Y}{\tau_{YA}}\right). \tag{8}$$

Desired Orchards ($O^*$) is given by the product of Orchards ($O$) and the Effect of Expected Profitability on Orchards ($E_{PO}$). We capture the Effect of Expected Profitability on Orchards ($E_{PO}$) using a logistic function. Desired Young orchards ($Y^*$) is determined by the product of the Desired Growth Rate ($GR^*$) and Growth Delay Time ($\tau_{GD}$):

$$O^* = O \cdot E_{PO}, \tag{9}$$

$$Y^* = \tau_{GD} \cdot GR^*. \tag{10}$$

The Desired Growth Rate ($GR^*$) is given by the sum of Expected Loss Rate ($LR$) and Adjustment for Orchards ($AO$), Eq. (6), and it should be nonnegative. The expected Loss Rate ($LR$) is the exponential smooth of Discard Rate ($DR$) over the Time to Adjust Expected Loss Rate ($\tau_{LR}$):

$$GR^* = Max\left(0, LR + \frac{O^* - O}{\tau_{AO}}\right), \tag{11}$$


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$$\frac{dLR}{dt} = \frac{DR - LR}{\tau_{LR}}. \tag{12}$$

*Profitability*

The profitability sector describes revenues, costs, expected profitability, and the effect of expected profitability on orchards. Revenues ($R$) are determined by the multiplication of pistachio production ($PP$) and the sales price of pistachios ($p$). The price ($p$) is set in international markets, reported in U.S. dollars, and considered to be exogenous to the model (Iranian Pistachio Association, 2013):

$$R = PP \cdot p. \tag{13}$$

The Expected Revenue ($ER$) is given by an exponential smooth of actual revenues ($R$) over the Time to Adjust Expected Revenue ($\tau_{ER}$):

$$\frac{dER}{dt} = \frac{R - ER}{\tau_{ER}}. \tag{14}$$

Total Cost ($TC$) is the sum of Cost of Water ($CW$), Cost of Labor ($CL$), and Cost of Orchards maintenance ($CO$). The Cost of Water ($CW$) is the exponential smooth of the Indicated Cost of Water ($CW_{Ind}$) over the Time to Adjust Cost of Water ($\tau_{CW}$). The indicated water cost ($CW_{Ind}$) is inversely proportional to normalized water height ($h$) with a sensitivity factor ($\lambda$) determined by model calibration:

$$TC = CW + CL + CO, \tag{15}$$

$$\frac{dCW}{dt} = \frac{CW_{\mathrm{Ind}} - CW}{\tau_{CW}}, \tag{16}$$

$$CW_{Ind} = CW_0 \cdot h^{\lambda}. \tag{17}$$

Normalized water height ($h$) is given by the water Height ($H$) divided by the Maximum water Height ($H_{max}$), while water height ($H$) is determined by groundwater volume ($GW$) divided by aquifer surface area ($S$), which is 4000 $km^2$ (Torabi, 2016):

$$h = \frac{H}{H_{max}}, \tag{18}$$

$$H = \frac{GW}{S}. \tag{19}$$


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The Cost of Labor ($CL$) is the exponential smooth of the Indicated Cost of Labor ($CL_{Ind}$) with the Time to Adjust the Cost of Labor ($\tau_{CL}$). Similarly, the Cost of Orchards ($CO$) is the exponential smooth of the Indicated Cost of Orchards ($CO_{Ind}$) with the Time to Adjust the Cost of Orchards ($\tau_{CO}$). We assume that the Indicated Cost of Labor ($CL_{Ind}$) and the Indicated Cost of Orchards ($CO_{Ind}$) increase with Iran's inflation rate ($\Delta CPI$):

$$\frac{dCL}{dt} = \frac{CL_{Ind} - CL}{\tau_{CL}}, \tag{20}$$

$$CL_{Ind} = CL \cdot (1 + \Delta CPI), \tag{21}$$

$$\frac{dCO}{dt} = \frac{CO_{Ind} - CO}{\tau_{CO}}, \tag{22}$$

$$CO_{Ind} = CO \cdot (1 + \Delta CPI). \tag{23}$$

We used Iran's inflation and exchange rates in the calculations because farmers face production costs in the Iranian currency (Rials), but collect revenues in U.S. dollars, since pistachios are exported and sold abroad. To make the revenue and cost comparable, we convert production costs into U.S. dollars by considering Iran's inflation and exchange rates. The online supporting information provides more details about the formulation. The simulated values are first calculated in the local currency and then converted to the U.S. dollars using data for the foreign exchange rate. The initial values are determined based on inflation-rates data and experts' opinions. The Expected Cost ($EC$) is specified by the exponential smooth of Total Costs ($TC$), over the Time to Adjust Expected Costs ($\tau_{EC}$), estimated using model calibration:

$$\frac{dEC}{dt} = \frac{TC - EC}{\tau_{EC}}. \tag{24}$$

The Expected Profitability Fraction ($EP$) is determined by the Expected Profitability, that is, the gap between Expected Revenues ($ER$) and Expected Costs ($EC$), divided by a Reference Revenue ($R_R$). The reference revenue provides a reference threshold for producers' reactions to profitability; a higher reference value suggests that producers will expect higher profitability levels to expand cultivation efforts:

$$EP = \frac{ER - EC}{R_R}. \tag{25}$$

Following Repenning (2002) and Kapmeier and Gonçalves (2018), we capture the Effect of Expected Profitability on Orchards ($E_{PO}$) using an


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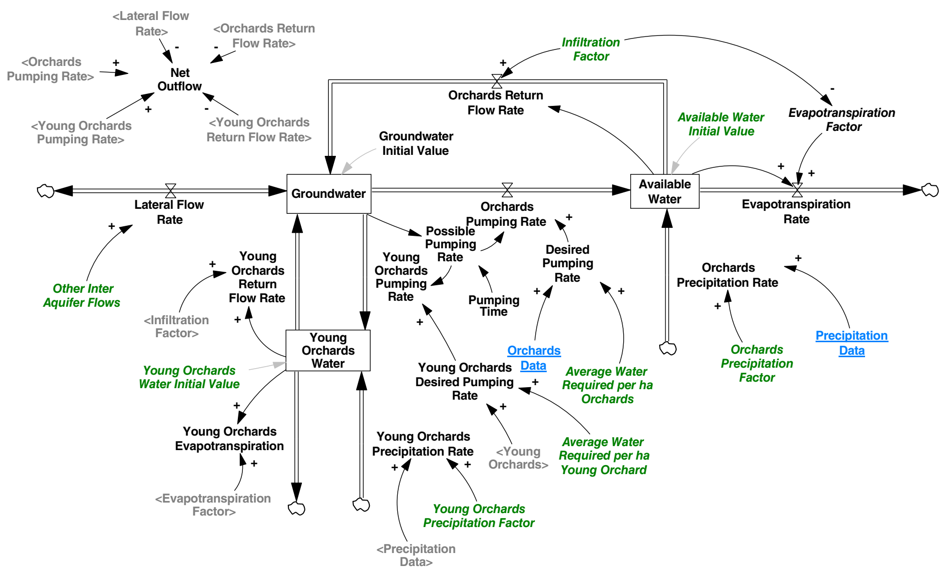


Fig. 7. Stock and flow diagram for the water sector. Model constants are in italic and data variables are underlined [Color figure can be viewed at wileyonlinelibrary.com]

increasing logistic function, where a high level of profitability results in a higher level of the desired orchards:

$$E_{PO} = B_L + (B_U - B_L) \cdot \left\{ 1 - \frac{e^{s(EP-i)}}{1 + e^{s(EP-i)}} \right\}. \tag{26}$$

The lower bound ($B_L$) and the upper bound ($B_U$) capture the minimum and maximum effect of expected profitability on the orchards' desired level. The inflection point ($i$) determines the threshold above which farmers are willing to plant and expand their orchards. The slope ($s$) reflects the farmers' sensitivity towards the intensity of plantation, that is, how they behave concerning a change in the Expected Profitability Fraction (*EP)*. Full model calibration determines the values of the parameters in the logistic function (i.e. $B_U$, $B_L$, $i$, $s$).

*Water resources*

The water sector describes the stock and flow structure associated with groundwater and water used for irrigation and production (Figure 7). The Orchards Water Pumping Rate ($WR_O$) and Young Orchards Water Pumping Rate ($WR_Y$) deplete the stock of Groundwater ($GW$), while the Return Flow Rate from Orchards ($RR_O$) and Return Flow Rate from Young Orchards ($RR_Y$) increase it. The groundwater is also affected by underground Other inter-aquifer Flow Rates ($OR$):


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$$\frac{dGW}{dt} = OR + RR_O + RR_Y - WR_O - WR_Y. \tag{27}$$

The Orchards Water Pumping Rate ($WR_O$) is given by the product of the Desired Water Orchards Pumping Rate ($WR_O{}^*$) and the Effect of Groundwater on Pumping Rate ($E_{GP}$). The Desired Orchards Water Pumping Rate ($WR_O{}^*$) is determined by the Average Water required per Orchard hectare ($WH_O$) multiplied by the number of mature Orchards ($O$). The Effect of Groundwater on Pumping Rate ($E_{GP}$) is captured by an increasing s-shaped function where low groundwater reduces pumping. The online supporting information provides more details on the formulation of this function:

$$WR_O = WR_O^* \cdot E_{GP}, \tag{28}$$

$$WR_O^* = O \cdot WH_O. \tag{29}$$

Similarly, the Young Orchards Water Pumping Rate ($WR_Y$) is given by the product of the Desired Young Orchards Water Pumping Rate ($WR_Y{}^*$) and the Effect of Groundwater on Pumping Rate ($E_{GP}$). The Desired Young Orchards Water Pumping Rate ($WR_Y{}^*$) is specified by the Average Water required per Young orchard hectare ($WH_Y$) multiplied by the Young Orchards area ($Y$):

$$WR_Y = WR_Y^* \cdot E_{GP}, \tag{30}$$

$$WR_Y^* = Y \cdot WH_Y. \tag{31}$$

Return Flow Rate from Orchards ($RR_O$) is given by the stock of Available Water ($AW$) adjusted by the constant Infiltration Factor ($IF$). Return Flow Rate from Young Orchards ($RR_Y$) is given by the stock of Young Orchards Water ($YW$) adjusted by the constant Infiltration Factor ($IF$). The Other inter-aquifer flow Rate ($OR$) is constant determined by full model calibration:

$$RR_O = AW \cdot IF, \tag{32}$$

$$RR_Y = YW \cdot IF. \tag{33}$$

The Available Water ($AW$) used for production and irrigating the orchards is a stock increased by Orchards Water Pumping Rate ($WR_O$) and Water Precipitation Rate ($WP$) and decreased by Evapotranspiration ($VR$) and Return Flow Rate ($RR$). Likewise, the stock of Young Orchards Water ($YW$) only used for young orchards irrigation is increased by Young Orchards Water Pumping Rate ($WR_Y$) and Water Precipitation Rate ($WP$) and decreased by Evapotranspiration ($VR$) and Return Flow Rate ($RR$):


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$$\frac{dAW}{dt} = WR_O + WP - VR - RR, \tag{34}$$

$$\frac{dYW}{dt} = WR_Y + WP - VR - RR. \tag{35}$$

The Water Precipitation Rater for Orchards ($WP_O$) is given by the product of the Orchards' Precipitation Factor ($PF_O$) and the Average Annual Precipitation ($AP$) (Healy, 2010; Yeh and Famiglietti, 2009). Likewise, the Water Precipitation Rater for Young Orchards ($WP_Y$) is given by the product of the Young Orchards' Precipitation Factor ($PF_Y$) and the Average Annual Precipitation ($AP$):

$$WP_O = AP \cdot PF_O, \tag{36}$$

$$WP_Y = AP \cdot PF_Y. \tag{37}$$

The Evapotranspiration Rate ($VR$) captures the joint effects of evaporation of water from soil and the transpiration from plants; the Evapotranspiration Rate ($VR$) is equal to the product of Available Water ($AW$) and the Evapotranspiration Factor ($EF$):

$$VR = AW \cdot EF. \tag{38}$$

*Pistachio production*

The production sector models the relationship between inputs and outputs. We assume that the aggregate level of pistachio production follows the generalized form of a Cobb–Douglas production function (Cobb and Douglas, 1928; Douglas, 1976; Meeusen and van Den Broeck, 1977):

$$PP = TFP \cdot \left(\frac{AW}{R_{AW}}\right)^{\alpha} \cdot \left(\frac{O}{R_O}\right)^{\beta} \cdot \left(\frac{L}{R_L}\right)^{\gamma}. \tag{39}$$

Here, $TFP$ is the Total Factor Productivity, $AW$, $O$, and $L$ correspond to the Water used for irrigation, bearing Orchards, and Labor, respectively, each divided by corresponding constant reference values. A relatively higher reference value represents a lower impact of input on production.

Constants α, β, and $\gamma$ are output elasticities with respect to each input. The output elasticities capture the sensitivity of output to changes in the level of inputs. We estimate the constants $TFP$, α, β, $\gamma$, $R_{AW}$, $R_O$, and $R_L$ through partial and full model calibration.


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In previous sections, we have discussed Orchards and Water in detail. Below, we provide some discussion of Labor and Total Factor Productivity, the remaining components of our Cobb–Douglas production function.

### *Labor*

We treat Labor (*L*) as exogenous in our model. Labor comprises activities such as pruning, applying fertilizers and pesticides, and harvesting. Although in some areas, such as California, using machines is more efficient (Ferguson and Haviland, 2016); due to the low cost of manual labor in Iran, workers are highly involved in pistachio production.

### *Total factor productivity*

Total Factor Productivity (*TFP*) aggregates the effects of various exogenous variables, including fertilizers, pesticides, and managerial experiences. There are two reasons for this aggregation. First, most of these effects can be captured as a residual explaining the amount of output that cannot be measured through direct calculations using only inputs (Hulten, 2001). Second, the Cobb–Douglas function is a hypothetical function and does not precisely explain the mechanisms and processes of transforming inputs to output, although it is an appropriate estimation of aggregate output that has long been used by economists (Arrow *et al.*, 1961; Cobb and Douglas, 1928; Douglas, 1976; Farrell, 1957). Therefore, assuming the Total Factor Productivity (*TFP*) as a proxy of other variables is plausible. The online supporting information provides details related to output elasticities and returns to scale.

## Parameter estimation

The proposed model describes and aggregates relationships that have been documented in the literature. However, much of the evidence for the relationships is case specific and fragmented. To test and build confidence in our model, we evaluate the ability of individual relationships to operate simultaneously in a wide range of settings and their interactions ability to replicate the observed dynamics properly (Forrester, 1979; Naylor and Finger, 1967; Van Horn, 1971). To statistically estimate the individual relationships in the model and assess the extent to which the model quantitatively replicates the observed behavior, we compared the behavior of the model against the available data. Due to a large number of parameters, we started by partial model calibration to gain insights about the feasible intervals for parameter values. After conducting the partial estimation for each sector, we determine the values


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for parameters using full model calibration (Homer, 2012; Morecroft, 1985; Oliva and Sterman, 2001).

The objective of the estimation, given the structure of the model, is to minimize the weighted sum of squared errors between the simulated values and the corresponding data: Orchards Data (*OD*), Groundwater Data (*GWD*), Net Outflow Data ($\Delta GWD$), and Production Data (*PD*):

$$\underset{x\in\mathbb{R}}{Min}\left(w_1\cdot\sum_{t=1}^{n}(O(t)-OD(t))^2+w_2\cdot\sum_{t=1}^{n}(GW(t)-GWD(t))^2\right.$$
$$\left.+w_3\cdot\sum_{t=1}^{n}(\Delta GW(t)-\Delta GWD(t))^2+w_4\cdot\sum_{t=1}^{n}(P(t)-PD(t))^2\right). \tag{40}$$

Subject to: Full model specification

where $x$ represents all the parameters in the model to be estimated. The sum of squared errors is correspondingly weighted by the inverse of the sample standard errors of the actual data for each variable. The properly weighted sum of squares allows us to calculate 95 percent confidence intervals for each estimated parameter. We apply Powell optimization to solve the minimization problem (Eq. (40)) using the maximum of 50,000 iterations and 100 random restarts to avoid local minima.

### *Partial model calibration*

We isolate each sector of the model for the partial model calibration using data variables as endogenous inputs. For the orchards and profitability sectors, we use historical values of pistachio production, pistachio price, and orchards to estimate adjustments times ($\tau_{GD}$, $\tau_{OA}$, $\tau_{YA}$, $\tau_{AD}$, $\tau_{LR}$, $\tau_{ER}$, and $\tau_{EC}$), components of the logistic function ($R_R$, $i$, $s$, $B_U$, $B_L$), and the parameters for the water cost function ($CW_0$ and $\lambda$). We coupled partial calibration for the orchards and profitability sectors because no intermediate data variable is available to allow individual isolation. The water sector uses historical orchards area to estimate the average water required for orchards ($WH_O$), water required for young orchards ($WH_Y$), other interaquifer flows (*OR*), precipitation, evapotranspiration, and infiltration factors (*PF*, *EF*, *IF*). The production sector utilizes the historical orchards area, labors, and changes in the groundwater water volume ($\Delta GWD$) to estimate the Total Factor Productivity (*TFP*) output elasticities ($\alpha$, $\beta$, and $\gamma$) and inputs reference values ($R_{AW}$, $R_O$, and $R_L$).

Despite being extremely helpful, partial calibration involves challenges. It is particularly difficult to partially calibrate the model around groundwater, as it entails the young orchards pumping rate. The young orchards pumping rate depends on the stock of young orchards and the average water required for young orchards. Because there are no time-series data on young orchards, we cannot include the effects in the partial-model calibration. To resolve this


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Table 1. Estimated parameters from full-model calibration with 95% confidence intervals

| Parameter | | Eq. # | Lower bound of 95% CI | Full model estimate | Upper bound of 95% CI |
|---|---|---|---|---|---|
| Orchards | | | | | |
| $\tau_{GD}$ | Growth Delay Time (years) | 4 | 5.000 | 5.169 | 6.175 |
| $\tau_{OA}$ | Orchards Adjustment Time (years) | 6 | 4.117 | 4.580 | 5.000 |
| $\tau_{YA}$ | Young Orchards Adjustment Time (years) | 7 | 0.250 | 0.250 | 3.900 |
| $\tau_{AD}$ | Average Discard Time (years) | 5 | 20.000 | 20.000 | 22.333 |
| $\tau_{LR}$ | Time to Adjust Expected Loss Rate (years) | 12 | 12.004 | 41.515 | 120.000 |
| $\tau_{ER}$ | Time to Adjust Expected Revenue (years) | 14 | 2.861 | 5.000 | 5.000 |
| $\tau_{EC}$ | Time to Adjust Expected Costs (years) | 24 | 0.250 | 0.250 | 0.879 |
| $Y_i$ | Young Orchards Initial Value (hectares) | OS[a] | 34,473.2 | 43,770.2 | 51,530.4 |
| Profitability | | | | | |
| $R_R$ | Reference Revenue (dollars) | 25 | 1.187E+08 | 1.400E+08 | 1.754E+08 |
| $i$ | Inflection Expected Profitability (dimensionless) | 26 | 0.410 | 0.467 | 0.500 |
| $s$ | Normal Slope Expected Profitability (dimensionless) | 26 | −0.500 | −0.499 | −0.406 |
| $B_U$ | Max Effect of Expected Profitability (dimensionless) | 26 | 2.282 | 2.316 | 2.350 |
| $B_L$ | Min Effect of Expected Profitability (dimensionless) | 26 | 0.035 | 0.066 | 0.097 |
| $CW_0$ | Initial Water Cost ($/MCM[b]) | 17 | 90,930.5 | 100,000 | 100,000 |
| $\lambda$ | Water Cost Sensitivity (dimensionless) | 17 | −9.971 | −8.264 | −6.756 |
| $P_0$ | Initial Pistachio Price ($/Tonne) | OS | 3926.68 | 4500.00 | 4500.00 |
| Water Resources | | | | | |
| $WH_O$ | Water requirements of Orchards (MCM/ha/year) | 29 | 0.0046 | 0.0050 | 0.0053 |
| $WH_Y$ | Water requirements of Young Orchards (MCM/ha/year) | 31 | 0.0017 | 0.0024 | 0.0033 |
| $PF_O$ | Orchards Precipitation Factor (MCM/mm) | 36 | 0.000 | 0.000 | 0.283 |
| $PF_Y$ | Young Orchards Precipitation Factor (MCM/mm) | 37 | 0.438 | 0.872 | 1.292 |
| $IF$ | Infiltration Factor (1/year) | 32 | 0.472 | 0.500 | 0.500 |
| $OR$ | Other inter-aquifer flow Rate (MCM/year) | 27 | 81.563 | 99.693 | 117.529 |
| $AW_O$ | Available Water Initial Value (MCM) | OS | 450.671 | 552.023 | 653.251 |
| $AW_Y$ | Young Orchards Available Water Initial Value (MCM) | OS | 0.000 | 0.012 | 263.976 |
| Pistachio Production | | | | | |
| $TFP$ | Total Factor Productivity (Tonne/Year) | 39 | 173,600 | 179,173 | 180,603 |
| $\alpha$ | Output Elasticity of Water (dimensionless) | 39 | 0.484 | 0.495 | 0.508 |
| $\beta$ | Output Elasticity of Orchards (dimensionless) | 39 | 1.045 | 1.344 | 1.584 |
| $\gamma$ | Output Elasticity of Labor (dimensionless) | 39 | −0.248 | −0.192 | −0.129 |
| $R_{AW}$ | Water Reference Value (MCM) | 39 | 5530.3 | 5857.8 | 6234.3 |
| $R_O$ | Orchards Reference Value (hectares) | 39 | 81,007.7 | 82,745.3 | 84,713.1 |
| $R_L$ | Labor Reference Value (people) | 39 | 28,695.8 | 33,833.0 | 39,257.9 |

aOS: The equation is in the online supporting information.
bMCM: Million Cubic Meters.

issue, we use the simulated values of young orchards from the partial calibration of the orchards and profitability sectors (see the online supporting information for the details about the partial model calibration).

The partial model calibrations examine the ability of individual relationships between variables to replicate the observed dynamics given the actual data. However, since the partial tests cut major feedback in the system, it is necessary to examine the ability of the full model in replicating the actual dynamic behavior.


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Table 2. Summary statistics for full-model calibration

| | Weight | MAPE (%) | RMSE | MAE/ μ (%) | Theil's inequality statistics Bias | Unequal Variation | Unequal Covariation |
|---|---|---|---|---|---|---|---|
| Orchards (*O*) | 7.57E-05 | 2.52 | 3173.27 | 2.53 | 0.000 | 0.063 | 0.936 |
| Groundwater (*GW*) | 6.82E-04 | 0.09 | 36.89 | 0.09 | 0.080 | 0.007 | 0.911 |
| Net Outflow ($\Delta GW$) | 1.97E-02 | 22.74 | 38.07 | 19.97 | 0.000 | 0.172 | 0.827 |
| Production (*P*) | 3.40E-05 | 30.16 | 22,364.7 | 25.46 | 0.000 | 0.309 | 0.690 |

There are 32 observations for each variable.

### *Full model calibration*

Table 1 represents the estimated values for parameters, including 95 percent confidence intervals. The estimated values for some parameters are similar to the values in the partial model tests. Furthermore, most of the estimated parameters demonstrate tight confidence intervals and are within a plausible range. In particular, the growth delay time ($\tau_{GD}$) is around 5 years, which is around the estimated value via partial model calibration and is within the range reported in the literature (Ferguson and Haviland, 2016).

Regarding the profitability, the minimum ($B_L$) and maximum ($B_U$) effects are around 0 and 2.3, indicating that extremely high profitability results in more than double the level of desired orchards, while extreme loss causes the level of desired orchards to become approximately zero. Considering the minimum ($B_L$) and maximum ($B_U$), the inflection point ($i$), which is around 0.47, suggests that farmers increase their orchards at profitability higher than 47 percent. The normal slope, −0.49, indicates moderate sensitivity of farmers in response to changes in profitability.

Concerning the water resources, the precipitation factor ($PF_Y$) is around 0.9. This parameter converts the reported precipitation measurements in millimeters to the volume of water in Million Cubic Meters ($10^6$ x $m^3$ or MCM) that either infiltrated to the aquifer or evaporated (Healy, 2010; Karamouz *et al.*, 2020). The estimated parameter denotes the average volume of 65 million cubic meters ($10^6\ m^3$) of rainfall, aligned with the average reported values over time (Iran Water Management Institute, 2014). Moreover, the estimated infiltration factor (*IF*) is 0.5, close to the reported observed values.

In the production sector, the estimated total factor productivity (*TFP*) is around the average production captured from the data. The sum of output elasticities is around 1.65, suggesting an increasing return to scale for the Cobb–Douglas production function—1 percent increase in the production


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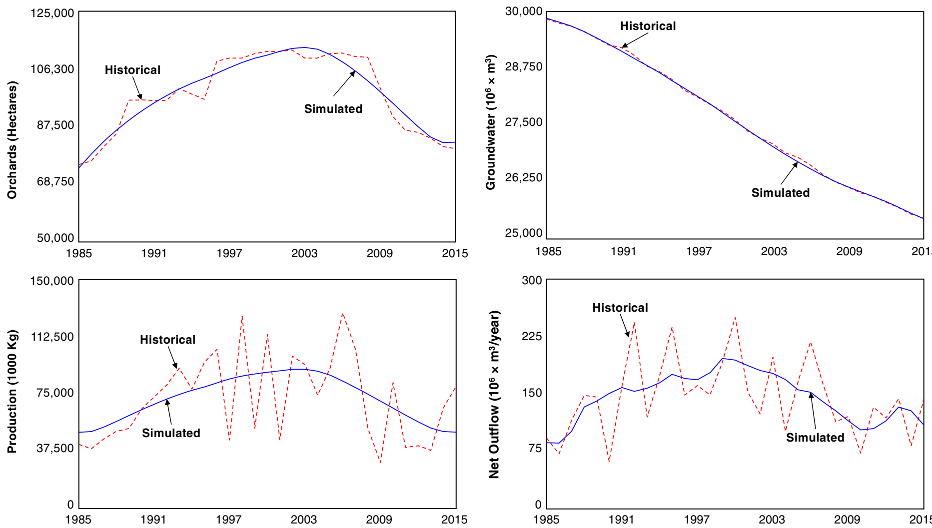


Fig. 8. Full model results plotted against the historical data [Color figure can be viewed at wileyonlinelibrary.com]

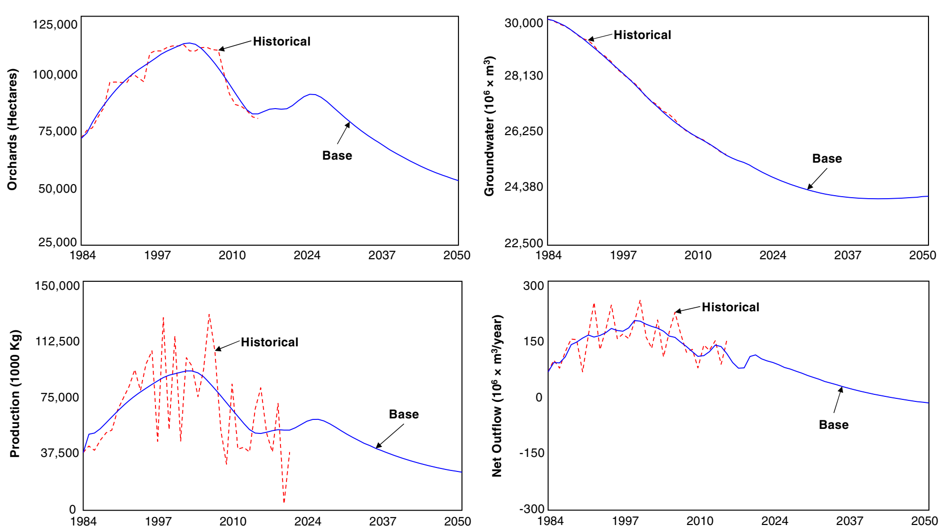


Fig. 9. Base run. Predictions for selected variables (from top left to bottom right): orchards, groundwater, net outflow, and production [Color figure can be viewed at wileyonlinelibrary.com]

inputs results in around 1.65 percent increase in the output. The negative value for the output elasticity of labor ($\gamma$) indicates the diminishing returns of the labor effect on the production.

Table 2 represents summary statistics, including the goodness-of-fit measures, the Mean Absolute Percent Error (MAPE), Root Mean Square Error (RMSE), Mean Absolute Error over the Average (MAE/μ), and the Theil's


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inequality statistics (e.g. bias, unequal variation, and unequal covariation) for full model calibration. The MAPE and is MAE/μ less than 30 percent for all four variables. Moreover, Theil's inequality statistics for all

Table 3. Overview of policies

| Overall goal | Policy | Mechanisms | Examples in practice | Relevant Literature |
|---|---|---|---|---|
| Support farmers and pistachio production | (1) Water Transfer | Water transfer rate (MCM/Year) Water transfer price ($/MCM) | 45 billion $m^3$ per year in China (Jiang, 2009) 176 billion $m^3$ per year in India (Joshi, 2013) | – |
| | (2) Drip irrigation | Drip Irrigation Water Reduction (MCM/Hectares/ Year) Drip irrigation efficiency (Dimensionless) | 28% efficiency enhancement in China for maize production Tian *et al.* (2017) | – |
| | (3) Subsidies | Subsidies Percentage Change (Dimensionless) | $1.7 billion in China to support grain self-sufficiency (Huang *et al.*, 2011) | – |
| Preserve and improve groundwater storage | (4) Income tax | Tax rate (Dimensionless) | – | Certain tax rates result in increased total social benefits; an experimental study (Duke *et al.*, 2020) |
| | (5) Water pricing | Change in Water Price (Dimensionless) | €0.014 per $m^3$ for water extraction over 1000 $m^3$ in France (Graveline, 2020) | 10 cents increase in water price; a simulation study of South African agricultural water consumption (Letsoalo *et al.*, 2007) |
| | (6) Land purchasing | Orchards reduction rate (Hectares/Year) | – | Land retirement in Kern County, California; a field-level scenario analysis (Bourque *et al.*, 2019) Land purchasing policy in Rafsanjan, Iran; a simulation study (Mehryar *et al.*, 2019) |


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variables show low bias and unequal variation. Such results indicate an unsystematic error (Sterman, 1984; Theil, 1966). The variable for production, *P*, represents the highest error, because the Cobb–Douglas function cannot replicate the alternate bearing nature of pistachio trees, meaning that the yield fluctuates naturally between "on" and "off" years. Moreover, we did not include the temperature variations as an input for the production function.

Figure 8 compares the simulated and actual data for the full model calibration using estimated parameters. As suggested by the summary statistics in Table 2, all variables, limited by the model structure and plausible parameter values, display a good fit to the historical data, simultaneously reproducing the trend in all dependent variables. Specifically, the simulated groundwater properly replicates the historical reported values, although they are normally hard to measure, containing high uncertainty. The Iranian Water Resources Management Company provides only a point estimate for the measure, but no uncertainty range.

## Base run

The base run (Figure 9) begins from 1984 and continues through 2050. Based on average historical values, we assume that the foreign exchange rate and inflation rate grow annually by 20 percent (Central Bank of Iran, 2019). We also assume that the pistachio price remains constant equal to the present-day price; however, we test various possible scenarios in the sensitivity analysis. More details on assumption and the sensitivity analysis are explained in the online supporting information. The simulation shows that farmers continue to reduce orchards due to the low profitability. By 2050, orchards area decreases, reaching to about 53,000 ha. On the one hand, the declined orchard area causes the average production to reach about 25,000 t per year in 2050, resulting in lower revenue.

On the other hand, fewer orchards are followed by lower water consumption. In 2050, the inflow to the groundwater becomes higher than the pumping rate, and the aquifer is recharged approximately 20 million cubic meters of water per year, which is not so much. Consequently, the groundwater storage stabilizes and reaches to near 24,000 million cubic meters in 2050, preventing further water decline and increase in water costs.

Contrary to the existing mental models, that all orchards will dry in the following decade (Jalalpour, 2016), the base run shows the orchards area will not completely vanish. After 2020, there is a steeper reduction in the orchards area; however, around 2050, farmers stop cutting off further orchards, and the level of orchards reaches to a stable level. The reason


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behind this phenomenon is that as farmers diminish their orchards, they also reduce their groundwater consumption. Over the years, the groundwater condition improves, mitigating water-scarcity issues. Since more water availability results in lower water costs, the pistachio production becomes favorably profitable, and producers maintain their orchards.

## Policy considerations

In this section, we present two opposing sets of policies concerning agricultural water management. Over the last several decades, Iran has been one of the leading global producers of pistachio, receiving significant policy support from its government. Early on, government policies were motivated mainly by economic considerations. More recently, government policies are better aligned with sustainable growth, considering not only economic aspects, but also environmental ones (e.g. groundwater availability) associated with pistachio production.

Based on the literature and existing reports, we explore the impact of two opposing sets of policies aimed at agricultural activities. The first set of policies seeks to stimulate pistachio production by (i) increasing available water resources through transfers, (ii) enhancing production yield through drip irrigation, while decreasing water consumption, and (iii) reducing production costs through subsidies. The second set of policies seeks to limit agricultural activities and improve groundwater conditions by (iv) imposing financial disincentives through taxation, (v) regulating water prices, and (vi) limiting cultivated area through land purchase schemes. Table 3 presents an overview of all policies studied. For each policy, we evaluate their impacts on pistachio orchards and pistachio production, available groundwater, and net water outflow. We explore the impact of the policies for 30 simulated years (from 2020 to 2050), assuming constant inflation and exchange rates at 2020 levels.

### *Water transfer*

A water-transfer policy seeks to support pistachio producers facing water shortages and increasing water costs by bringing water from regions with abundant water resources. This policy attempts to maintain agricultural activities, preventing the orchards from drying out.

There are several examples of government-led water-transfer projects around the world. In China, the $62 billion South-to-North Water Transfer Project is intended to provide up to 45 billion m$^3$ of water per year for domestic and industrial uses, by 2050 (Jiang, 2009). In India, the $120 billion National River Linking Project is estimated to transfer annually 176 billion m$^3$ of water from north-east to western and southern India, by 2050 (Joshi, 2013).


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For Rafsanjan, a water-transfer project would require more than 300 km of pipes and is expected to cost around $2 billion to provide the infrastructure needed for transferring water to the region (Iranian Parliament Research Center, 2014). However, the details of this project, particularly the amount of water being transferred per year, are not yet available. Representatives in the parliament are willing to help farmers mitigate existing barriers to agricultural activities. But while a water-transfer policy has several advocates who believe that water transfer can help groundwater recovery (IRNA, 2019b), some environmentalists highly doubt the long-term benefits of this plan (EghtesadOnline, 2017). In contrast, farmers perceive a water-transfer policy favorably, willing to purchase the transferred water to increase production rates. As one of the farmers put it:

> "Most of producers are suffering from water scarcity to the extent that they are willing to provide water to their orchards by any means. One of the farmers, with the permission he received, has built a 70-kilometer pipe infrastructure, treats the municipal wastewater, and uses it to irrigate his orchards."

To model this policy, we assume that the annual amount of water transferred to be a fraction of the annual average of historical water consumption. Over the past 30 years, the average pumping rate has been around 500 million $m^3$ (Iran Water Management Institute, 2014). Therefore, we assume that the policy will annually provide 100 million $m^3$ of water required for irrigating the orchards, aligned with the reported predicted values (Entekhab, 2019). We also assume that the government will charge, on aggregate, $150′000 per million $m^3$ of water, which is approximately one third of the current cost of acquiring water determined locally through supply and demand.

### *Drip irrigation*

Drip-irrigation systems are targeted and more efficient, meaning they can increase crop yield while reducing water consumption. Unlike traditional flood-irrigation methods, drip-irrigation systems allow water slowly to drip to the roots and are installed either above the soil or buried below the surface.

Since the 1950s, drip irrigation has been applied successfully in arid regions or areas suffering from water shortages (Ayars *et al.*, 1999). In the United States, during the 1980s and 1990s, the area using drip irrigation increased fivefold, reaching over 1 million hectares, or 5 percent of the total irrigated area (Ayars *et al.*, 1999). By 2018, that number had increased to near 2 million hectares, or over 10 percent of the total irrigated area (United States Department of Agriculture, 2018). The benefits of drip-irrigation systems are well documented in the literature. In the North China Plain, Tian *et al.* (2017) show that compared with the flood irrigation, maize


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yield increases by 28 percent using drip-irrigation systems. In Queensland, Australia, Pendergast *et al.* (2019) report that combined with air injection, drip irrigation results in an average 18.5 percent increase in chickpea yields. In Lebanon, Nouri *et al.* (2019) show that combined with mulching, drip irrigation reduces water consumption by 4.7 percent for various crops. Another study reports that by decreasing the evapotranspiration using drip-irrigation systems, water consumption can be reduced by 50 percent depending on the temperature variation (Wang *et al.*, 2020).

In Rafsanjan, only a few hectares of orchards are now using drip-irrigation systems. However, to increase the efficiency and reduce the water consumption, the government intends to provide subsidies of $500 per ha to support the transition from flood- to drip-irrigation methods (IRNA, 2018) as regional officials believe that modern drip-irrigation technology can help improve the groundwater condition and resolve the water scarcity issues. As one of the farmers explains:

> "I have not yet implemented drip irrigation in my orchards. If I have drip irrigation, I might say, in line with policymakers' opinion, yes, I should be able to increase production per hectare [while keeping the current orchards area]. But how do I know that I adhere to this principle? If I am using drip irrigation and can develop new orchards, I have a thirst to do so."

To model the impact of a drip-irrigation policy, we assume that total water required for orchards is reduced by 25 percent, and the yield is increased by 25 percent.

### *Subsidies*

A government subsidy policy promotes agricultural activities by making them more attractive to producers and reducing barriers to entry (Ellis, 1992). A government subsidy policy could take the form of directly supplying some production inputs (e.g. fertilizers) or reducing the costs of specific inputs (e.g. reduced gasoline price). Such policy seeks to reduce production costs, making them economically viable.

There have been numerous examples of agricultural subsidies around the world. During the 1960s and 1970s, the Indian government supported the farmers by providing them credit, fertilizers, and irrigation (Fan *et al.*, 2008). In China, the government raised agricultural subsidies from $12 million in 2003 to $1.7 billion in 2004 to support grain self-sufficiency and farm income (Huang *et al.*, 2011).

Over the past decades, the Iranian government has supported the development of pistachio orchards and pistachio production through subsidy policies, resulting in a lower cost of production than other producers around the world (Mehryar *et al.*, 2017; Mehryar *et al.*, 2019). While producers welcome


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further government support, through tax subsidies and financial support, they also blame the authorities for water shortages. As the head of Farmer House in Bahreman city (adjacent to Rafsanjan) puts it (Iranian Labour News Agency, 2018):

> "Groundwater has been severely reduced due to the negligence of provincial officials, the water department, and the Ministry of Energy … Our request to the government is to provide free loans to farmers so that they can resume their activities by relaunching water pumps' engines."

To model the impact of a subsidy policy, we assume that 35 percent of the total production costs are covered by the government.

*Income tax*

An income tax policy demotes agricultural activities by making them less attractive to farmers and increasing barriers to entry. Income taxes directly affect revenue, influencing the profitability on which producers rely to make investment decisions for cultivation. Such policy seeks to preserve and improve the groundwater storage by controlling the orchards area.

Studies examining the tax regulations have mainly focused on the tax regimes supporting agricultural activities (OECD, 2020). Lately, however, scholars have started focusing on tax policies seeking to improve and preserve the environment. In France, a recent study shows that flexible tax rates can improve groundwater storage (Graveline, 2020). An experimental study demonstrates that taxation can enhance groundwater resources while increasing the net social benefits (Duke *et al.*, 2020).

For the last several decades, the Iranian government has actively supported agricultural activities by not taxing farmers (Iranian National Tax Administration, 2015). Recently, the government has sought to pass a law that would effectively tax pistachio producers (Donya-e-Eqtesad, 2018), causing worry among them.

The new tax law has not yet been passed, and it is not clear its level. To model this policy, we assume a 20 percent tax on revenue, which according to Mansour (2015) is plausible for a developing country.

*Water pricing*

A water-price policy seeks to reduce groundwater extraction by increasing water costs. Such policy can involve diverse economic instruments such as price increase or water tax.

Scholars have studied the water-price policy for different regions around the world. A simulation study shows that if the South African government increases the water price by 10 African cents per $m^3$, agricultural water


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Table 4. Parameter changes and policies impacts in 2050[a]

| Run | Parameters Changed | Value (Base case value) | Orchards (Hectares) | Groundwater (MCM[b]) | Net Outflow (MCM/Year) | Production (Tonne/ Year) |
|---|---|---|---|---|---|---|
| Base values in 2020 | - | - | 84,467 | 25,006 | 105 | 52,417 |
| | | | Impact in 2050 | | | |
| Base | - | - | 53,140 [−37%] | 24,103 [−4%] | −19 [−118%] | 24,739 [−53%] |
| (1) Water transfer | Water transfer rate (MCM/Year)<br>Water transfer price ($/MCM) | 100 (0)<br>1.5E+05 (0) | 62,852 [−25%] | 24,973 [−0.1%] | −39 [−137%] | 37,293 [−29%] |
| (2) Drip irrigation | Drip Irrigation Water Reduction (MCM/Hectares/ Year)<br>Drip irrigation efficiency (Dimensionless) | 0.25 (0)<br>0. 25 (0) | 66,889 [−21%] | 24,519 [−2%] | −22 [−121%] | 35,085 [−33%] |
| (3) Subsidies | Subsidies Percentage Change (Dimensionless) | 0.35 (0) | 78,197 [−7%] | 22,273 [−11%] | 41 [−61%] | 46,859 [−11%] |
| (4) Income tax | Tax rate (Dimensionless) | 0.20 (0) | 48,265 [−43%] | 24,449 [−2%] | −32 [−130%] | 21,101 [−60%] |
| (5) Water pricing | Change in Water Price (Dimensionless) | 0.15 (0) | 49,521 [−41%] | 24,353 [−3%] | −29 [−128%] | 22,021 [−58%] |
| (6) Land purchasing | Orchards reduction rate (Hectares/ Year) | 2500 (0) | 51,965 [−38%] | 24,457 [−2%] | −19 [−118%] | 23,788 [−55%] |

aNumbers inside the brackets denote percentage changes from the base case.
bMCM: Million Cubic Meters (million m3).

consumption can be reduced by 6 percent (Letsoalo *et al.*, 2007). In France, all farmers that withdraw more than 1000 m$^3$ must pay a fixed tax of €0.014 per m$^3$ for extra water extraction (Graveline, 2020).

In Rafsanjan, the current cost of water acquisition is around $0.4 per m$^3$. Although Iranians have long been recognized for efficient allocation and regulation for agricultural water consumption, the Iranian governments have had little impact on water use for pistachio production over the past few decades (Madani, 2014). However, the local authorities in Rafsanjan hope to impose new regulations on water prices by using new technologies such as modern water meters and effective monitoring of water wells (Abdullahi, 2007). A water-pricing policy has a similar effect as an income tax policy on orchards and groundwater.


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Fig. 10. First policy set compared to the base run: (1) water transfer, (2) drip irrigation, (3) increased subsidies and their effects on orchards, groundwater storage, production, and net outflow [Color figure can be viewed at wileyonlinelibrary.com]

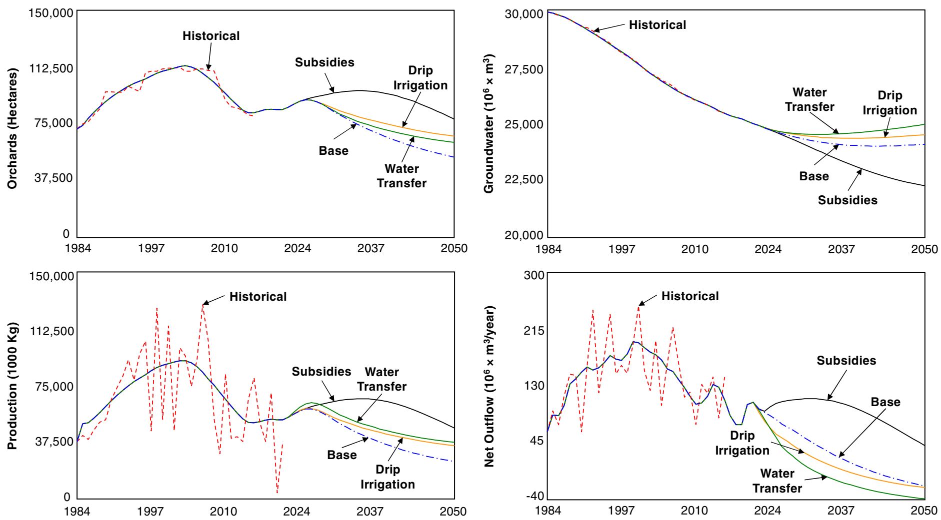
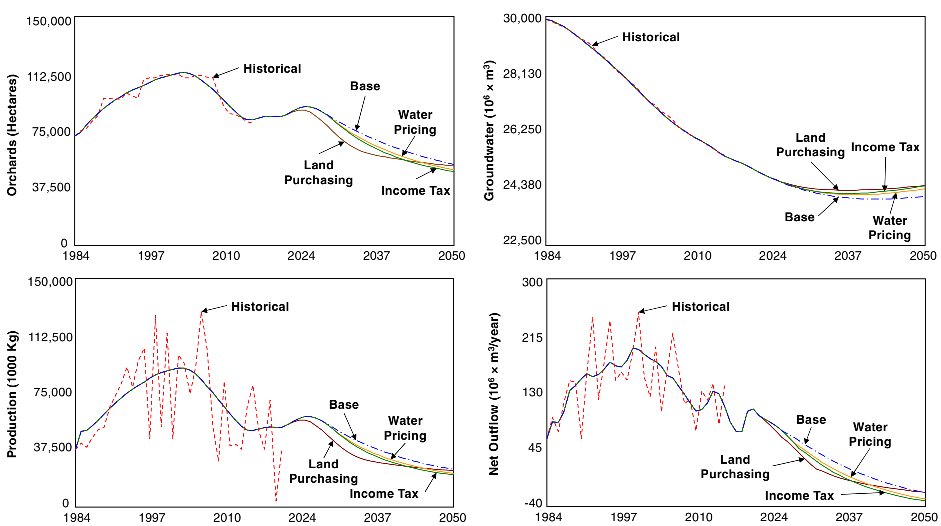



Fig. 11. Second policy set compared to the base run: (4) income taxes, (5) water pricing, (6) land purchasing and their effects on orchards, groundwater storage, production, and net outflow [Color figure can be viewed at wileyonlinelibrary.com]




To model the impact of water-price policy, we assume that the government increases the current water price by 15 percent.

## *Land purchasing*

A government land-purchasing policy seeks to limit the cultivated area by reducing the bearing orchards. Such policy aims to lower groundwater


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Table 5. Impact of joint policies in 2050[a]

| Run | Details of run | Orchards (Hectares) | Groundwater (MCM[b]) | Net Outflow (MCM/Year) | Production (Tonne/Year) |
|---|---|---|---|---|---|
| Base values in 2020 | – | 84,467 | 25,006 | 105 | 52,417 |
| | | Impact in 2050 | | | |
| Base | – | 53,140 [−37%] | 24,103 [−4%] | −19 [−118%] | 24,740 [−53%] |
| (7) Joint Set 1 | Combines policies (1), (2), and (3) | 163,664 [+94%] | 22,460 [−10%] | 161 [+53%] | 163,897 [+213%] |
| (8) Joint Set 2 | Combines policies (4), (5), and (6) | 45,296 [−46%] | 24,922 [−0.3%] | −37 [−135%] | 18,961 [−64%] |

aNumbers inside the brackets denote percentage changes from the base case.
bMCM: Million Cubic Meters (million m3).

consumption because of decreased orchards area. Under this policy, the government would buy orchards and transform them into nonagricultural lands to prevent further irrigation.

The land-purchasing policy is relatively rare and new. A field-level analysis of Kern County, California, shows that land retirement can contribute to higher groundwater recharge (Bourque *et al.*, 2019). In Iran, the government rented around 50,000 ha from farmers to prevent water consumption and improve Lake Urmia's condition (IRNA, 2014).

In Rafsanjan, financial losses due to high water costs and low pistachio prices make a land-acquisition program an attractive proposition to producers (Mehryar *et al.*, 2019). Currently, there is no available information on the government's intention to implement it and skepticism among producers on its appeal:

> "A similar plan to reduce agricultural lands was implemented on Lake Urmia, with partial success. But it is very difficult to implement in the long run."

To model this policy, we assume that the government reduces the orchards area for 10 consecutive years with an annual rate of 2500 ha starting from 2020. At the same time, we also assume that the government prevents new plantations.


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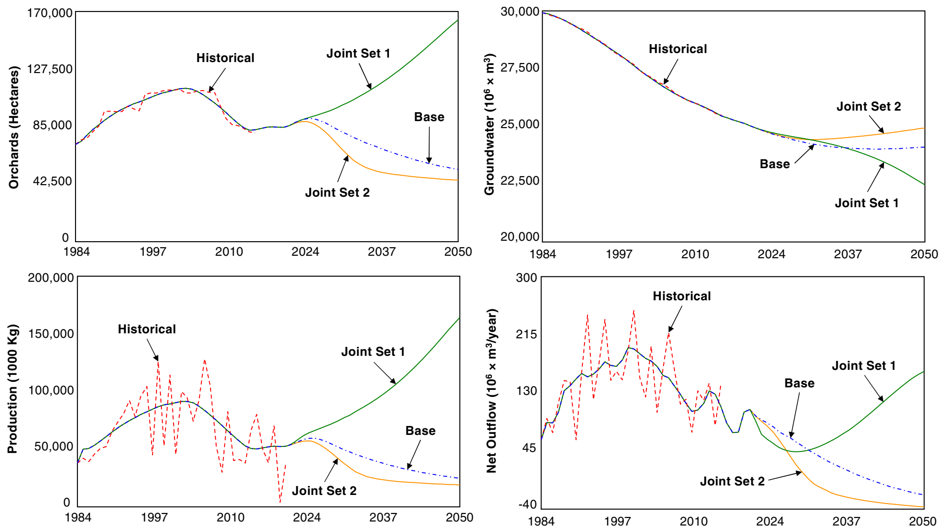


Fig. 12. Effect of joint policies set 1 and 2 on orchards, groundwater storage, production, and net outflow [Color figure can be viewed at wileyonlinelibrary.com]

## Policy results

In this section, we test the simulated impact of different policies on the main variables of the system. While the first set of policies seeks to stimulate pistachio production, the second set of policies attempts to limit it. Table 4 summarizes details on the changes in model parameters for each policy as well as the overall impact by 2050 on key performance indicators (KPIs) such as orchards area (in hectares), groundwater level (in million $m^3$), net water outflow (in million $m^3$/year), and pistachio production (in tons/year).

Figure 10 shows the results for the first set of policies. The focus of these policies is to support farmers by providing more water resources, increasing efficiency, or reducing production cost via financial subsidies. In policy (1), growth in available water through water transfer results in immediate increase in production and profitability followed by an expansion in orchards area. Under policy (2), adoption of drip irrigation leads to lower water consumption and also higher production yields, resulting in growth in profitability and orchards expansion. The subsidies policy (3) helps farmers in the short term by reducing production costs, which leads to growth in orchards area and in groundwater consumption. In the long term, however, groundwater levels deteriorate reducing also the level of orchards.

Figure 11 shows the results for the second set of policies. These policies focus on maintaining or improving groundwater conditions by either regulating the orchards area or introducing financial disincentives. Under policy (4), the income taxes imposed by the government reduce profitability in the short term. However, as farmers discard part of their lands, and decrease


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water consumption (and pistachio production), the region experiences an improvement in groundwater levels. In the long term, the orchards area returns to original levels. In policy (5), the government increases the price of water, increasing total production costs and decreasing profitability, prompting farmers to discard part of their lands. The policy results in reduced irrigation requirements and groundwater-level recovery. Policy (6) reduces the orchards area by regulating both planting and discard rates. Reduction in planted area leads to immediate improvement of groundwater storage.

The outcome of individual policies is sensible. Policymaking often combines multiple policies with similar goals. Below, we take a closer look at the combined effect of similar policies. Policy set 1 (7) seeks to support farmers and agricultural activities. In contrast, policy set 2 (8) focuses on preserving groundwater resources. Table 5 reports the joint effect of the two sets of policies on KPIs by 2050.

Figure 12 shows the behavior of the key variables regarding the joint effects of each policy set. Combining policies (1), (2), and (3) increases the support for farmers and agricultural activities, almost doubling the orchards area and tripling the production. Combining policies (4), (5), and (6) manifests success in preserving and improving the groundwater, even with continuous water consumption by the existing orchards.

However, the joint effect of policy set 1 shows a counterintuitive behavior. Although each policy from set 1 individually reinforces agricultural activities and help maintain groundwater resources, the combination of these policies causes unintended consequences. The reason is while policies (1) and (2) provide more water resources due to water transfer and reduce water consumption because of drip irrigation, they cause a huge orchards expansion, specifically when combined with subsidies, policy (3). But since there is more than a 5-year delay for orchards to become mature, the groundwater level improves in the short term. As young orchards become mature, after around 10 years, in 2030, the groundwater starts to decline significantly because of increased water demand.

## Discussion

Water plays a critical role in pistachio production (Ferguson and Haviland, 2016), and water management is a crucial issue to create a balance between economic growth and the environmental preservation (Famiglietti, 2014), particularly in complex social-ecological systems (SESs) (Ostrom, 2009). Despite getting much attention in the agricultural water-management literature, the management of such resources in relation to social and economic activities is not well understood (Jeong and Adamowski, 2016); only a few systematic studies cover the topic, and still they have little or no quantitative analysis (Fernández and Selma, 2004). In


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this article, we use system dynamics to analyze the dynamic interaction between economic growth (through agricultural activities) and environmental degradation (through overexploitation of water). We examine different policies (e.g. supporting agricultural activities or seeking groundwater preservation) and assess their long-term impact in Rafsanjan. Our research yields the following insights.

First, government policies should consider simultaneously economic development (e.g. through agricultural activities involving orchard area and pistachio production) and environmental conditions (e.g. through groundwater levels). Focusing solely on agricultural activities, critical to the regional economy (EghtesadOnline, 2017; IRNA, 2019b), will likely compromise available resources in the long run. Government policies that seek to mitigate limited groundwater supply (e.g. water transfer, drip irrigation) work only in the short term, as they eventually allow growth in the cultivated area, which results in greater water demand in the long term. Recently, these findings have been confirmed for Zayandeh-Rud in the central plateau of Iran (Sharifi *et al.*, 2021). Previous studies also suggest that in case of limited resources, particularly with negative feedback loops and considerable delays, growth can lead to overshoot and oscillation around the carrying capacity (Sterman, 2000; Mirchi *et al.*, 2012). SESs similar to Rafsanjan, hoping to grow their economies inattentive to resource limits and delays, will likely face growth with overshoot and oscillation.

Second, policies must be supported by different stakeholders over long periods of time. The ability to preserve scarce resources and improve conditions in complex systems is contingent on understanding and accepting worse-before-better behavior (Gonçalves, 2011; Repenning and Sterman, 2002). Unlike organizational systems that require continuous top-management support to achieve innovative goals (Repenning, 2002), SESs need sustained advocacy from multiple stakeholders, including resource users (Madani and Dinar, 2012; Ostrom, 2008, 2009). In the case of Rafsanjan, unpopular policies (e.g. income tax and water pricing) will likely translate in significant producer resistance. Still, to ensure groundwater-resources recovery, pistachio producers must learn to accept the negative short-term impact that will make way for the positive long-term environmental improvement.

In summary, our research informs SESs stakeholders on the trade-offs between economic growth and its environmental impacts. The research also develops a regional-level model capable of evaluating the long-term impact of various policies on different aspects of the system.

Despite its usefulness, a number of opportunities for improvement remain. In the production sector, the model does not explicitly capture the effect of groundwater quality on pistachio production. As the groundwater level decreases, water quality deteriorates becoming more saline. Although pistachio trees tolerate some level of water salinity, after a threshold the reduced


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water-quality results in lower production yields. This effect was not captured in our model. Second, we also do not consider the effect of temperature variations on the production level (Ferguson and Haviland, 2016).

In the groundwater sector, we do not include the effect of groundwater decline on the infiltration rate. Studies suggest that a huge decline in the water table results in a lower capacity of an aquifer to infiltrate and absorb water in the long term (Motagh *et al.*, 2017; Rezaei, 2018). This is also not captured in our model. Instead, we consider a constant infiltration factor, because there is not much information about physical properties of Rafsanjan's aquifer. Furthermore, although there is always temperature variation in the region, we considered the evapotranspiration factor constant over time. Finally, the groundwater decline will significantly affect the humidity of the region in the long term, and it can result in regional climate change, which can reduce future precipitation.

In the profitability sector, we assume an aggregate logistic function to capture the decision of all producers. This simplification may not hold with high fidelity. Also, while our sensitivity analysis considers various price scenarios for future prices of pistachio, these are limited and not comprehensive. Next, while we capture the effect of expected profitability on desired orchards (based on revenue and costs), we cannot calibrate the model against cost data, as those data are not available.

Finally, for the orchards sector, due to lack of precise and clear data, we aggregate orchards at a high level (e.g. data for different stages of mature orchards is not available). Further data would improve the fidelity of our model.

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## Supporting information

Additional supporting information may be found in the online version of this article at the publisher's website.

**Appendix S1.** Supporting information


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