Supplementary for the article "From Aggregated Knowledge to Interactive Agents: an Agent Based Approach to Support Policy Making in Social-Ecological Systems"

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Overview, Design concepts and Details

1. Overview

1.1. Purpose

This model simulates different farmers' decisions and actions to adapt to the water scarce situation in Rafsanjan, Iran. This simulation helps to investigate how stakeholders' strategies may impact on macro-behavior of the system i.e. overall groundwater use change and emigration of farmers.

1.2. Entities, state variables, and scales

Agents: In this model, agents represent the total number of 154 farmers in three types of 21 large, 49 medium, and 84 small farmers. Their attributes are 1) their land size: 250ha > large farms > 80 ha > medium farms > 15 ha > small farms, 2) their sub-region, and 3) the actions they take.

Environment: Farmers are distributed across a stylized representation of the Rafsanjan landscape. As Rafsanjan is spatially heterogeneous, we distinguish nine sub-regions in the ABM, out of which two are representing non-vegetated area. Each sub-region consists of 15 by 15 cells, leading to a total of 45*45 cells. Each cell can have one farmer owning the cell; each farmer may have 1 or more cells. Agents are distributed equally across the seven regions and randomly within each region. Each cell represents 5ha of pistachio land. Cells are characterized by 1. Depth of groundwater level 2. Groundwater quality, 3. Productivity, 4. Land subsidence level, 5. Groundwater use 6. Well's depth, and 7. Allowed well's depth.

Temporal resolution: Time step is 1 month, and variables' changes are monthly or yearly. The temporal extend of the model is 15 years, i.e. 180 time steps.

1.3. Process overview and scheduling

Basically this model considers two main process in each time step:

1) Cells' update: There are two types of updates for cells' properties, 1) based on variables' dynamic changes collected from empirical data, e.g. groundwater level change and land subsidence level change, 2) based on impacts of actions –from previous step- on environment variables.

2) Agents' decision-making: First, all agents check their groundwater access. If an agent is not satisfied with the groundwater access, it enters the decision making process to adapt its groundwater access. Otherwise, it exits this time step.

2. Design concepts

2.1. Basic principles

The model is informed by Fuzzy Cognitive Mapping (FCM) models developed from time-series data (where formal data is available) and stakeholders' perception via interviews and mind mapping (for variables without formal data). From FCM models, we learn how macro level variables of a system, i.e. groundwater, regional economy, production, land use change, water management, human interventions etc., are influencing each other. Therefore, we know what are the causes and effects of different possible adaptive actions from farmers. Causes are the conditions of each action and effects are the impacts of each action on properties of agents or environment in the ABM. From FCM, we also have the weight or level of impacts of each action on other variables. Notice that in FCM we have the level of causal relations, but not the absolute value of each variables. Therefore, this models is meant to compare the impact of different adaptive strategies on specific variables rather than calculate or forecast the absolute value of each variables.

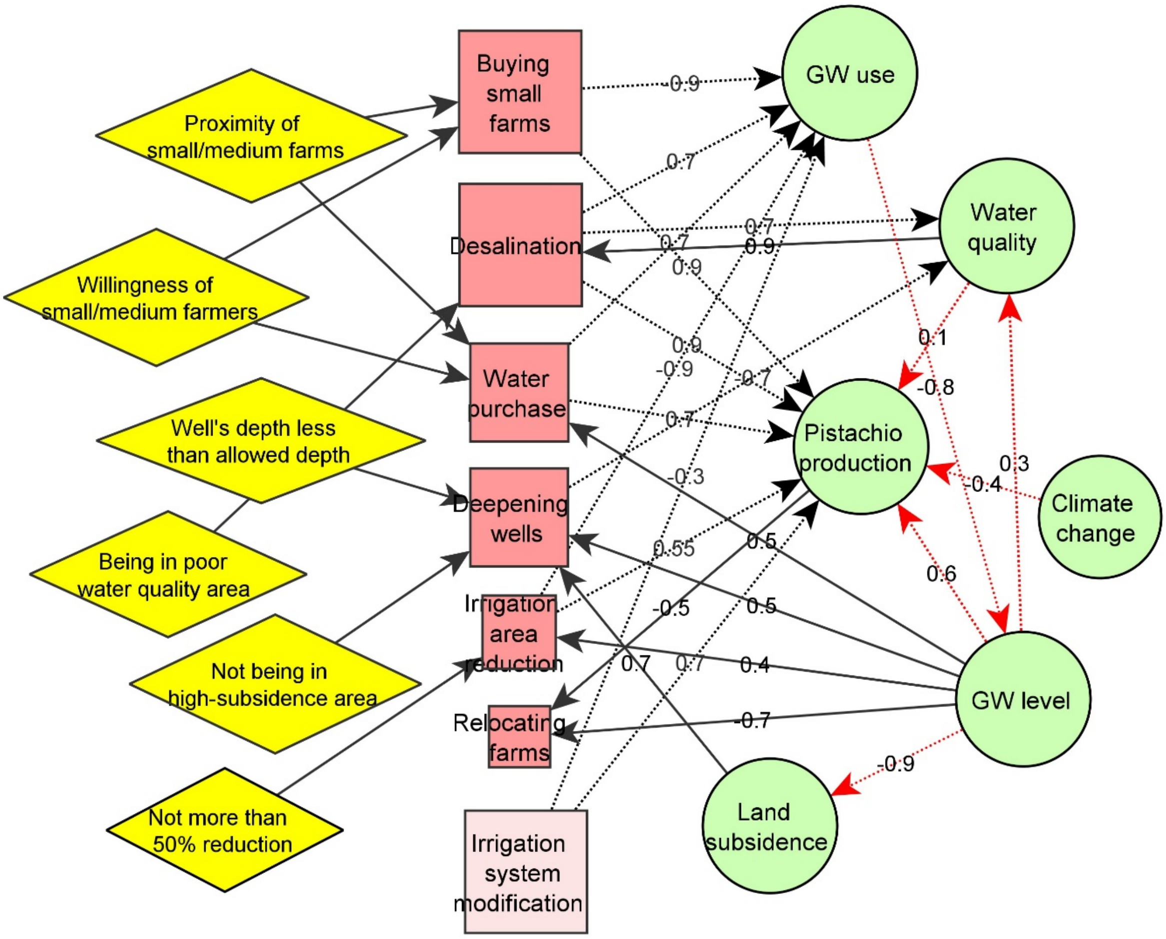

Figure1. Large-farmers' FCM combined with objective data. The red squares show farmers' actions and their size shows the number of farmers who took this action i.e. level of preference or priority of actions. Nodes with input to (yellow diamonds) and output from (green circles) actions represent conditions and impacts of those actions, respectively. Black and red lines represent perceived connections and data-driven connections, respectively. Solid and dashed lines show positive and negative causal connections, respectively.

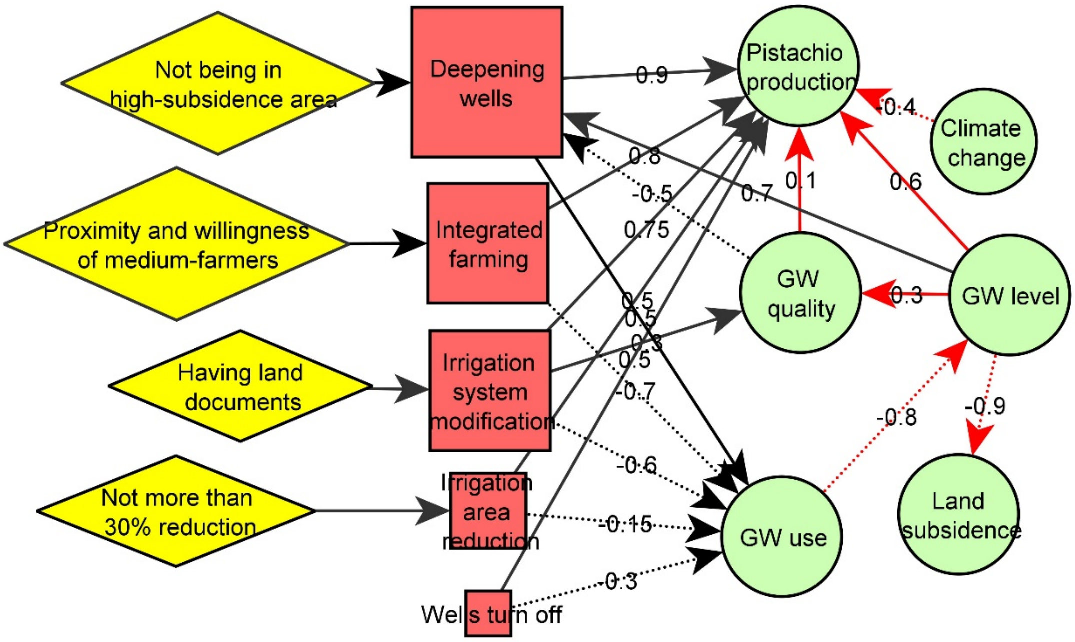

Figure2. Medium farmers' FCM combined with objective data

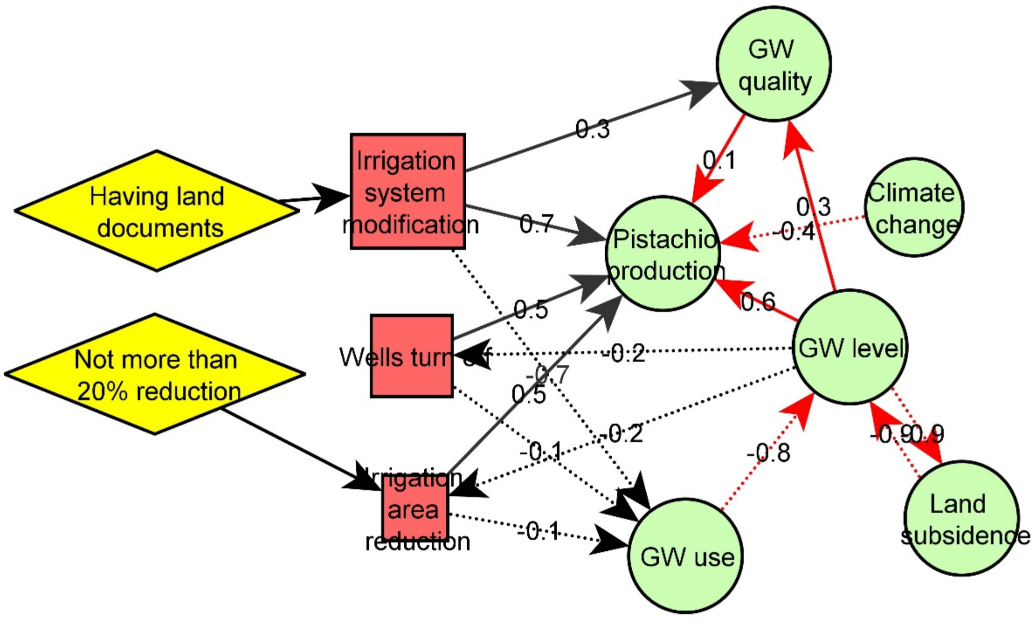

Figure3. Small-farmers' FCM combined with Objective data

2.2. Emergence

This model is designed to explore the relationship between farmers' adaptive actions towards water scarcity and two related emergent phenomena: overall groundwater use change and emigration of farmers. Overall groundwater use results from aggregated individual farmers' water use that may change over time due to their dynamic adaptive actions towards water scarcity and interactions with other farmers. Emigration of farmers results from their both groundwater access and interactions with other farmers.

2.3. Adaptation

All individual farmers do these adaptive actions to increase their ground water access or control their water use, and eventually increase their farms' production.

2.4. Objectives

Farmers want to keep their pistachio production and keep their access to groundwater for irrigation. If they are unsatisfied they leave and relocate their farms to the other regions.

2.5. Learning and Prediction

Individuals do not learn from their own experiences, i.e. positive or negative impacts of previous actions. Also, individuals do not predict or estimate future consequences of their decisions.

2.6. Sensing

Farmers have the full knowledge about the state of their groundwater access, their available options, their neighbors' willing to sell/buy land/water or integrate their lands, and their lands' groundwater quality, land subsidence, and allowed wells' depth. They do not have knowledge about the state of the overall groundwater level change in their region—which can help them in predicting future groundwater situation.

2.7. Interaction

Large farmers buy land and water from small and medium farmers. Medium farmers share their farms for efficient irrigation and farming. The structure of their social network for selling and buying land and water is emergent during the simulation. When the vulnerability of small or medium farmers becomes high, they will be willing to sell off their water and lands to the large farmers.

2.8. Stochasticity

Randomness is used in two processes: 1) executing of actions with the same priority, e.g. action number 3&4 in priority 2 of large farmers' actions list, and 2) the initial distribution of agents (farmers), farm sizes and initial values of parameters.

2.9. Collectives

There are no collectiveness among agents.

3. Details:

The model is implemented in NetLogo 6.0.1 (Wilensky, 1999) and available at ….

3.1. Initialization and input data

Initial patch properties (i.e. groundwater use, groundwater quality, land subsidence, ground water level, and well's depth) are extracted from GIS attribute data of 1369 wells in Rafsanjan collected in 2015 by Iran Water Resource Management Company (http://wrbs.wrm.ir/). In each sub-region an interval of initial values are calculated as explained below and them randomly distributed over the patches.

Initial groundwater use: groundwater use per hectare per month is calculated by:

$$\boldsymbol{Groundwater\ use}\ (\frac{\boldsymbol{mm^3}}{\boldsymbol{ha.mo}}) = \frac{\boldsymbol{Discharge} \times \mathbf{360} \times \boldsymbol{H} \times \mathbf{30}}{\boldsymbol{ha} \times \mathbf{10^6}}$$

Discharge (of wells' pumps) = volume of extracted water per second (m^3/s) for each well

H = Number of hours per day with wells' pump on (taken from GIS data for each well)

Ha = Pistachio land area covered with each well (taken from GIS data)

Initial wells' depth, *groundwater level* are calculated by their mean ± standard deviation

Initial land subsidence and groundwater quality are distributed in five levels of very low, low, medium, high and very high

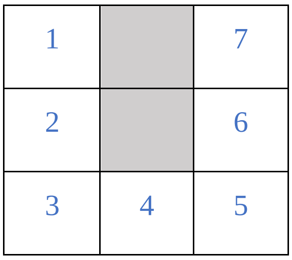

Figure 1. spatial representation of 7 regions

Table 1. Initial values of environment parameters.

	Location 1	**Location 2**	**Location3**	**Location4**	**Location 5**	**Location 6**	**Location7**
GW use (m^3/ha)	120	121	122	122	122	124	124
Well's depth (m)	95 - 100	105 - 110	130 - 140	130 - 140	135-145	140-150	125-135
GW level (m)	90	100	120	115	120	120	110
GW quality	Very low	Very low	high	Very high	Very high	medium	medium
Land subsidence	Low	low	Very high	Low	high	High-Very high	Very high

3.2. Sub models

Step 1) Update patches:

Indirect impacts of actions from previous time step are calculated at the beginning of the next step as follow:

Indirect impacts of actions are the impacts of variables affected by actions on other variables in FCM. To implement the impact of *Variable A* onto the *Variable B* (represented as $A \xrightarrow{w} B$) the value of *Variable B* in the new time step is calculated as:

$$B_{t+1} = B_t + B_t \times \frac{A_t - A_{t-1}}{A_{t-1}} \times w$$

Step 2) Agents' decision making:

2.1) each agent checks its groundwater access, based on:

GW access = depth of GW - Well's depth

If the agent is not satisfied it continues its decision making, otherwise it ends this time step.

The available actions that agents can take from are as follows:

- *Buying small/medium farms:* Buying farms from medium or small farmers who are not willing to continue pistachio production in their farms
- *Desalination*: set up desalination system on farms with poor water quality to remove salt and mineral from saline groundwater.
- *Water purchase*: Buying water from other farmers
- *Deepening wells:* Digging water wells to get access to groundwater
- *Irrigation area reduction*: shrinking (dry-off) small part of the farm to increase efficiency of water use for rest of the farm.
- *Integrating farms:* integrate irrigation system of some farms together to increase their efficiency.
- *Irrigation system modification*: changing traditional flood irrigation to drip irrigation.
- *Well's turn-off:* Increasing the wells' off-time over nights or winters
- *Relocating farms:* leave the region and buy farm in other areas with better water situation

2.2) Checks conditions of available actions: In this step, each agent check the actions' conditions through their priority order of actions. If the conditions are confirmed, it executes the action and if not it goes to the next action.

2.3) Action execution: Each agent execute possible actions. These executions depends on type of actions.

2.4) Implement impact of actions: execution of each action has specific level of impacts on other variables of the environment. This level of impact comes from the FCM model. Therefore, the state of influenced variables (affected variables in FCM) gets updated after execution of each action. Here we only implement the direct impact of actions on other variables. To implement the direct impact of actions X onto variables A of the FCM model (represented as $X \xrightarrow{w} A$), in each time step that action X is executed the value of *Variable A* in that time step is calculated as:

$$A_{t+1} = A_t + (A_t \times w)$$

For example, when we have *desalination* $\xrightarrow{0.7}$ *groundwater use* (in figure 2), whenever that action *desalination* is executed, it impacts *groundwater use* by 0.7 of its current value. So *Groundwater use* $_{t+1}$ = *Groundwater use* $_t$ + (*Groundwater use* $_t$ * 0.7).

2.5) At the end of each action list, if agent has no other actions left, it has to sell off its farms to large-farmers and leave if it belongs to small or medium holders. Large farmers have to relocate their farms to out of the region at the end of their action list.

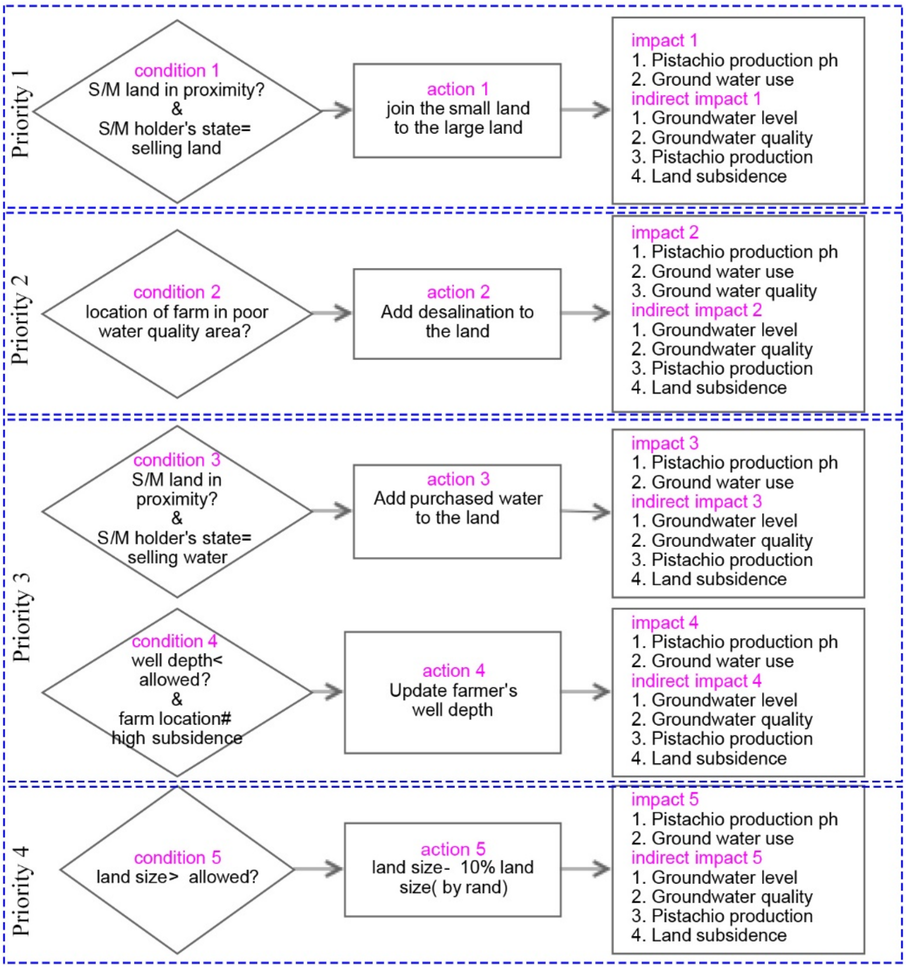

Figure 5. Conditions, actions and impacts for large-holders' set of actions

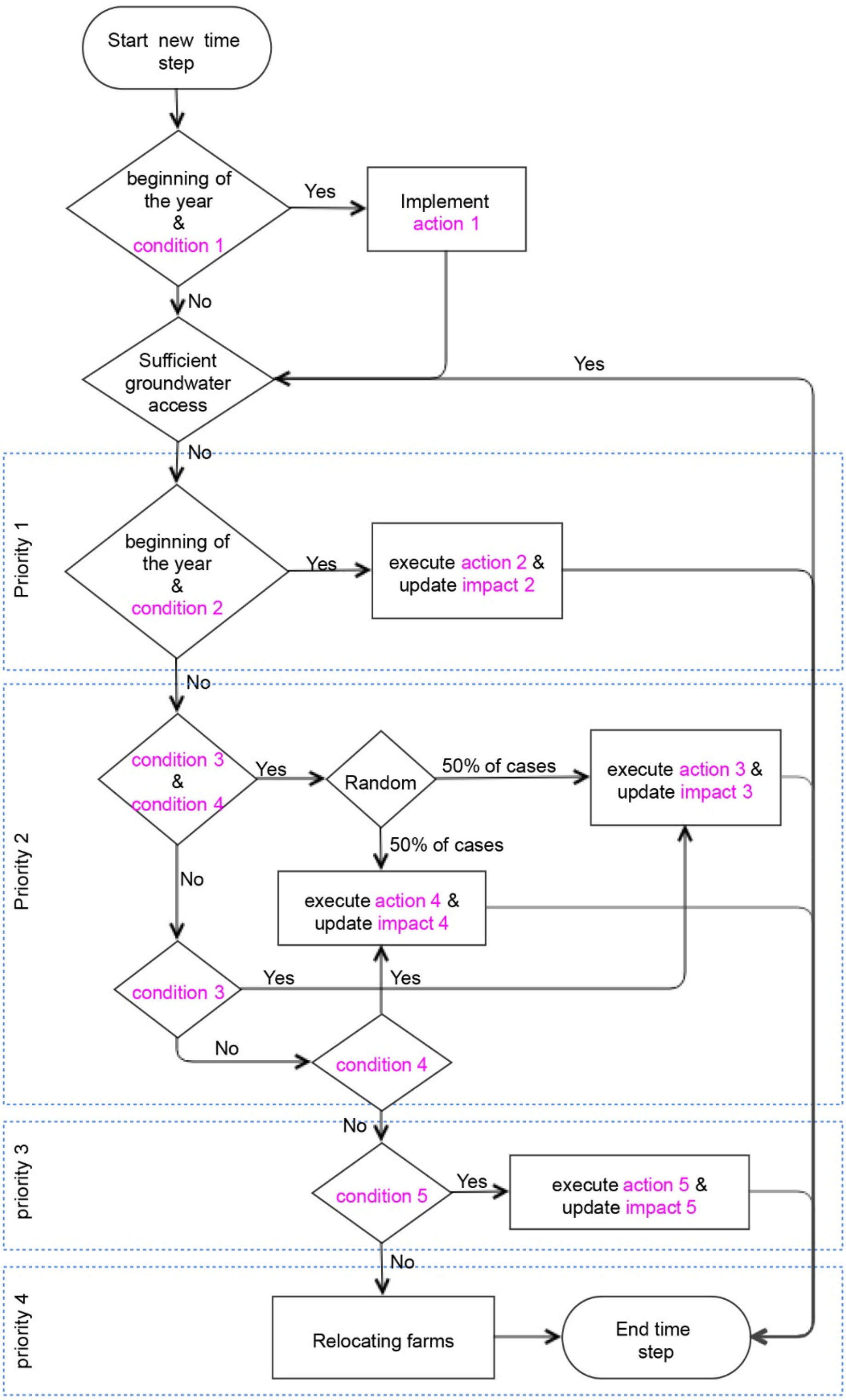

Figure 6. UML activity diagram of large farmers' behavioral rules in each time step

Table 2. Conditions, actions and impacts for large-farmers' set of actions

Action name	Conditions	Execution	impacts
1.Buying small/medium farms	Small land in neighborhood &	Change owner of small farm from small-farmer to the	On small-farm patches 1. GW-use= GW-use * 0.1

	Small-farmer is willing to sell-off land	large-farmer in neighbor	2. Productivity $_{t+1}$ = Productivity $_t$ + Productivity $_{(t)}$* 0.9
2. Desalination (one-time action)	Action 2 is available (has not been executed before) & Location of farm in poor GW quality area	Set action 2 not available for next steps	1. GW-use $_{t+1}$ = GW-use $_t$ + GW-use $_{(t)}$ * 0.7 2. Productivity $_{t+1}$ = Productivity $_t$ + Productivity $_{(t)}$* 0.9
3. Water purchase	Small land in neighborhood? & Small-farmer is willing to sell-off water	Add purchased water to the properties of farm-cluster	On small/medium farm: 1. GW-use $_{t+1}$ = GW-use $_t$ + GW-use $_{(t)}$ * 0.7 2. Productivity = 0 On large farm: Productivity $_{t+1}$ = Productivity $_t$ + Productivity $_{(t)}$* 0.2
4. Deepening wells	Well depth < allowed well depth & Farm location is not in high subsidence areas	Update the depth of the well	1. GW-use $_{t+1}$ = GW-use $_t$ + GW-use $_{(t)}$ * 0.5 2. Productivity $_{t+1}$ = Productivity $_t$ + Productivity $_{(t)}$* 0.7
5. Irrigation area reduction	Land size >= 50% initial land size (large farmers accept to shrink up to 50% of their lands)	Change 10% of farm patches to no-farm	On dried patches: 1.GW-use = 0 2. Productivity = 0 On farm patches: 1. GW-use $_{t+1}$ = GW-use $_t$ + GW-use $_{(t)}$ * (-0.1) 2. Productivity $_{t+1}$ = Productivity $_t$ + Productivity $_{(t)}$* 0.5
6. Relocating farms	No other available actions	Change all farm-patches to no-farm	1.GW-use = 0 2. Productivity = 0

Table 3. Conditions, actions and impacts for medium-farmers' set of actions

Action name	Conditions	Execution	Impacts
1.Deepening wells	Well depth < allowed well depth & Farm location is not in high subsidence areas	Update the depth of the well	1. GW-use $_{t+1}$ = GW-use $_t$ + GW-use $_{(t)}$ * 0.5 2. Productivity $_{t+1}$ = Productivity $_n$ + Productivity $_{(t)}$* 0.9
2.Integrating farming (By rand: change farmer’s	Medium land in neighbor? &		On both medium farms: 1. GW-use $_{t+1}$ = GW-use $_t$ + GW-use $_{(t)}$ * (-0.7)

state = integrating farm)	Neighbor medium-farmer is willing to land integration		2. Productivity $_{t+1}$ = Productivity $_{t}$ + Productivity $_{(t)}$ * 0.80
3. Irrigation system modification	Act 3 = 1 (available) & Farmer's land doc = 1 (available)	Add irrigation-modification to the properties of farm-cluster Set act 3 = 0	1. GW-use $_{t+1}$ = GW-use $_{t}$ + GW-use $_{(t)}$ * (-0.6) 2. Productivity $_{t+1}$ = Productivity $_{t}$ + Productivity $_{(t)}$ * 0.75
4. Irrigation area reduction	Land size >= 60% initial land size	Change 10% of farm clusters to no-farm	On dried patches: 1.GW-use = 0 2. Productivity = 0 On farm patches: 1. GW-use $_{t+1}$ = GW-use $_{t}$ + GW-use $_{(t)}$ * (-0.15) 2. Productivity $_{t+1}$ = Productivity $_{t}$ + Productivity $_{(t)}$ * 0.5
5. Sell land and relocation	Farmer's vulnerability = very high	Change all farm-cluster to no-farm	1.GW-use = 0 2. Productivity = 0

Table 4. Conditions, actions and impacts for small-holders' set of actions

Action name	Conditions	Execution	impacts
1.Irrigation system modification	Act 3 = 1 (available) & Farmer's land doc = 1 (available) & Random > 33%	Add irrigation-modification to the properties of farm-cluster Set act 3 = 0	1. GW-use $_{t+1}$ = GW-use $_{t}$ + GW-use $_{(t)}$ * (-0.7) 2. Productivity $_{t+1}$ = Productivity $_{t}$ + Productivity $_{(t)}$ * 0.7
2.well's turn off			1. GW-use $_{t+1}$ = GW-use $_{t}$ + GW-use $_{(t)}$ * (-0.3) 2. Productivity $_{t+1}$ = Productivity $_{t}$ + Productivity $_{(t)}$ * 0.7
4. Irrigation area reduction	Land size >= 70% initial land size	Change 10% of farm clusters to no-farm	On dried patches: 1.GW-use = 0 2. Productivity = 0 On farm patches: 1. GW-use $_{t+1}$ = GW-use $_{t}$ + GW-use $_{(t)}$ * (-0.1) 2. Productivity $_{t+1}$ = Productivity $_{t}$ + Productivity $_{(t)}$ * 0.5
5. Sell land and relocation	Farmer's vulnerability = very high	Change all farm-cluster to no-farm	1.GW-use = 0 2. Productivity = 0

Example: Large farmers have six possible adaptive action.

Action 1) is "*buying small/medium farms*" for which there are two conditions: there should be at least one small/medium land in the neighborhood of that agent's patch and that small farmer's state of "selling land" should be "on" that shows small farmer is willing to sell his/her land. When both of these conditions are confirmed, the small patch will be added to the large patch. By executing of this action 1. Ground water use of the small farms decreases by 90%, and 2. Pistachio production of small land increases by 90%.

Action 2) Desalination, for which there are two conditions: 1. this action should have not been implemented before, so, "desalination" property of farm should be equal to 0, and 2. the farm should be located in poor quality area. When both of these conditions are confirmed, the desalination is added to the land (desalination = 1), meaning not available for next time steps. By executing of this action 1. Pistachio production increases by 90%, and 2. Ground water use increases by 70%.

Action 3) Purchasing water, for which there are two conditions: there should be at least one small land in the neighborhood and that small farmer's state of "selling water" should be "on" that shows small-farmer is willing to sell his/her water. This property is related to the small farmer's level of vulnerability. When both of these conditions are confirmed, the "purchased water" gets added to the property of land. By executing of this action 1. Small/medium farm get no pistachio production, 2. Ground water use of small farms increases by 70%, and 3. Pistachio production of large farmers increases by 20%.

Action 4) deepening wells, for which there are two conditions: wells depth should not be equal or lower than the permitted depth and farm's location should not be in very high land subsidence areas. When both of these conditions are confirmed the wells depth gets update. By execution of this action 1) Ground water use increases by 50%, and 2) pistachio production increases by 70%.

Action 5: for which there is only one condition. As the last action before selling or relocating the lands, farmers start to shrink their farming area to increase efficiency of their production per hectare. However the land area reduction keeps happening till farmers still have some benefit of their lands. Otherwise they prefer to sell off land/water or relocate their land which can be more beneficial than shrinking and farming in the smaller lands. The threshold of shrinking lands is approximately 30% for small-holders, 40% for medium-holders and 50% for large-holders from FCM models. Therefore, if the agent's patches is bigger than minimum possible land ($p > 70\%/60\%/50\% * p_1$) then the agent's patches reduces by 10% ($p_{n+1} = 90\% * p_1$). By execution of this action 1) groundwater use and pistachio production of dried patches get equal to zero, 2) groundwater use of not dried patches decreases by 10%, and pistachio production of not dried patches increases by 50%.

Reference

WILENSKY, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling: Northwestern University, Evanston, IL.