ODD protocol of an Agent-Based Model of Campaign Based Watershed Management

1. Purposes

This model simulates the national CBWM program of Ethiopia to explore conditions that enhance coverage and quality of SWC structures. It analyzes the effect on the area of land covered and quality of SWC structures of (1) enhancing farmers' awareness and motivation, (2) establishing and strengthening micro-watershed associations, (3) introducing alternative livelihood opportunities, and (4) enhancing the commitment of local government actors. The ODD protocol is obtained from Grimm et al. (2010).

2. Entities, state variables, and scales

This model includes three agents (farmers, *Kebele* administrator, extension workers) and the physical environment that interact with each other. The physical environment is represented by 1089 fields, and each field is equal to 0.25 ha. Table 1 illustrates static and dynamic state variables of the fields. The values of the state variables are determined based on empirical study conducted in the *Kebeles* (villages) (Assefa et al. 2018).

Table 1: State variables of the field.

State variables	Values	Descriptions	Sources
Position (static)	Coordinates	-	Authors' judgment
Owned-by (static)	farmer code	Shows the farmer who owns this field. Set based on average farm size of the three *Kebeles*: 1.28 ha.	Household survey (Assefa et al. 2021a)
Slope (static)	%	The topography of the landscape is diffused from highest slope to lowest at initialization.	Authors' judgment
Land-use (static)	farmland or communal land	Shows whether this field is in the farmland or communal land. It is assigned to fields based on slope, where all fields with slope > 30% is considered communal land.	Gebreselassie et al. (2015)
Communal-micro-watershed? (dynamic)	true/false	Shows whether this field is inside the micro-watershed on communal land or not.	Google Earth Engine (Assefa et al. 2018)
Farmland-micro-watershed? (dynamic)	true/false	Shows whether this field is inside the micro-watershed on farmland or not.	Google Earth Engine (Assefa et al. 2018)
Communal-swc-cover? (dynamic)	true/false	Shows whether this field in micro-watersheds on communal land is covered with SWC structures or not.	Google Earth Engine (Assefa et al. 2018)
Farmland-swc-cover? (dynamic)	true/false	Shows whether this field in micro-watersheds on farmland is covered with SWC structures or not.	Google Earth Engine (Assefa et al. 2018)
Quality-SWC (dynamic)	0 -10	Shows initial quality of SWC structures. Model initiated in 2011/12 and average quality-SWC in 2015/16 is taken as initial quality-SWC for scenario analysis.	Authors' judgment
Micro-watershed-name (static)	field code	Shows name of micro-watersheds. The initial micro-watersheds were named "initial" and subsequently newly selected micro-watersheds were named: 0, 1, 2, etc.	Authors' judgment

Farmers are created and randomly distributed to farmland. All farmers own farmland in their vicinity. Some are members of micro-watershed associations. Table 2 shows static and dynamic state variables of the farmers. The values of most state variables were assigned to farmers randomly based on normal distributions with mean and standard deviations collected from the *Kebeles* (Assefa et al. 2021a; Assefa et al. 2021b).

Table 2: State variables of farmers.

	State variables	Values	Descriptions	Sources
	Farmers			
1	position (static)	Coordinates	Randomly distributed at initialization to fields on farmland.	Authors' judgment
2	own-farmland (static)	Patch-Id	Each farmer owns the fields or farmland in their vicinity; set based on average farm size of the three *Kebeles*.	Household survey (Assefa et al. 2021a)
3	education (static)	0-10	Shows the class farmers completed (0 = Illiterate, 10 = 10 and above); randomly distributed at initialization.	Household survey (Assefa et al. 2021a)
4	extent-off-farm-participation (static)	0-10	Shows the extent to which the farmer participates in off-farm activities; randomly distributed at initialization.	Household survey (Assefa et al. 2021a)
5	degree-participation-local-organizations (static)	0-10	The extent to which the farmer participates in different local organizations; randomly distributed at initialization.	Household survey (Assefa et al. 2021a)
6	perceived-performance-*Kebele*-administrator (static)	0-10	Shows farmer's perception of the commitment of *Kebele* administrator; randomly distributed at initialization.	RPG (Assefa et al. 2021b)
7	income (dynamic)	>= 0	Initial wealth (stock) of the farmer (birr); randomly distributed at initialization. Income initiated in 2011/12 using farm size (3000 birr per 0.25 ha) and average income in 2015/16.	Household survey (Assefa et al. 2021a)
8	social capital (dynamic)	0-10	Shows the position or status of the farmer in the *Kebele*; randomly distributed at initialization.	Household survey (Assefa et al. 2021a)
9	perception-watershed (dynamic)	0-10	Shows farmer's perception of the problem of watershed degradation and future benefits of the program; randomly distributed at initialization.	Household survey (Assefa et al. 2021a) and RPG (Assefa et al. 2021b)
10	membership-watershed-association (dynamic)	True / False	Shows whether this farmer is a member of micro-watershed association or not.	Household survey (Assefa et al. 2021a)
11	commitment-member-micro-watersheds (dynamic)	0-10	Shows the commitment of members of micro-watershed associations; randomly distributed at initialization.	Key informant interviews (Assefa et al. 2021a) and RPG (Assefa et al. 2021b)
12	measures (dynamic)	praise, no measure, aware, reprimand, punish	Shows the measure taken against this farmer by *Kebele* administrator. "No measure" at initialization.	Key informant interviews (Assefa et al. 2021a) and RPG (Assefa et al. 2021b)

The *Kebele* administrator has two static state variables: *position* (coordinates) and *commitment-of-kebele-administrator* (showing the commitment of *Kebele* administrator), ranging between 0 and 10. The extension workers have two similar static state variables: *position* (coordinates) and *commitment-extension-of-workers* (showing the commitment of the extension worker), ranging between 0 and 10. *Kebele* administrator and extension workers were placed around the center of the physical environment, and the values of their state variables (i.e. commitment) were set based on qualitative data obtained through key informant interviews (Assefa et al. 2021a) and Role-Playing game (Assefa et al. 2021b).

The model also considers 36 system parameters with their default values and ranges (Table 3).

Table 3: System parameters.

No	Parameters	Default	Range	Functions	Sources
1	number-of-farmers	180	100 - 250	Initial number of farmers.	Authors' judgment
2	n-new-members-association	10	0 - 30	Number of farmers organized to form a new micro-watershed association every year.	Authors' judgment
3	maximum-participation-cost	600	300 - 1000	The amount of money (birr) a farmer loses because of his highest possible level of participation.	Authors' judgment
4	maximum-punishment	600	300 - 1000	The amount of money (birr) a farmer will be fined if he does not participate at all.	Authors' judgment
5	income-poor-threshold	500	0 - 1000	Money (birr) below which farmers are considered to be poor and eligible for alternative livelihood activity.	Authors' judgment
6	extension-workers-move-selection-threshold	3	0 - 10	Score above which extension workers move to attend meeting with other agents to select new micro-watershed.	Authors' judgment
7	extension-workers-selection-threshold	7	0 - 10	Score above which extension workers are able to enhance farmers' perception of watershed degradation and future benefits of the program.	Authors' judgment
8	*kebele*-administrators-move-selection-threshold	3	0 - 10	Score above which *Kebele* administrators move to attend meetings with other agents to select new micro-watershed.	Authors' judgment

9	*kebele*-administrators-selection-threshold	6	0 - 10	Score above which *Kebele* administrators oblige farmers to select their preferred type of micro-watershed (farmland vs communal land).	Authors' judgment
10	perception-watershed-move-selection	5	0 - 10	Score above which farmers move to attend meetings with other agents to select new micro-watersheds.	Authors' judgment
11	perception-watershed-selection-threshold	7	0 - 10	Score above which farmers decide to select their preferred type of micro-watershed (farmland vs communal land).	Calibration
12*	w-perceived-performance-*kebele*-administrator-campaign	0.242	0 - 1	Relative influence of farmers' perceived performance of *Kebele* administrator during campaign participation.	Household survey (Assefa et al. 2021a)
13	w-off-farm-participation-campaign	0.385	0 - 1	Relative influence of the extent of participation in off-farm-activities during campaign participation.	Household survey (Assefa et al. 2021a)
14	w-distance-watershed-campaign	0.096	0 - 1	Relative influence of distance from micro-watersheds during campaign participation.	Household survey (Assefa et al. 2021a)
15	w-education-campaign	0.141	0 - 1	Relative influence of education during campaign participation.	Household survey (Assefa et al. 2021a)
16	w-social-capital-campaign	0.085	0 - 1	Relative influence of social capital during campaign participation.	Household survey (Assefa et al. 2021a)
17	w-degree-participation-local-organizations-campaign	0.039	0 – 1	Relative influence of degree of participation in local organizations during campaign participation.	Household survey (Assefa et al. 2021a)
18*	w-perception-watershed-campaign	0.012	0 - 1	Relative influence of perception of watershed degradation and future benefits of the program during campaign works.	Household survey (Assefa et al. 2021a)
19	extension-workers-move-campaign-threshold	5	0 - 10	Score above which extension workers move to newly selected micro-watershed during campaign participation.	Authors' judgment
20	*kebele*-administrators-move-campaign-threshold	7	0 - 10	Score above which *Kebele* administrators move to newly selected micro-watershed during campaign participation.	Calibration
21**	w-perceived-performance-*kebele*-administrator-maintenance	0.289	0 - 1	Relative influence of farmers' perceived performance of *Kebele* administrator during maintenance participation.	Calibration
22	w-off-farm-participation-maintenance	0.385	0 - 1	Relative influence of extent of participation in off-farm activities during maintenance activities.	Calibration
23	w-distance-watershed-maintenance	0.104	0 - 1	Relative influence of distance from micro-watersheds during maintenance participation.	Household survey (Assefa et al. 2021a)
24	w-degree-participation-local-organizations-maintenance	0.022	0 - 1	Relative influence of degree of participation in local organizations during maintenance participation.	Household survey (Assefa et al. 2021a)
25**	w-perception-watershed-maintenance	0.200	0 - 1	Relative influence of perception of watershed degradation and future benefits of the program during maintenance participation.	Calibration
26	extension-workers-move-maintenance-threshold	8	0 - 10	Score above which extension workers move to already developed micro-watershed during maintenance participation.	Authors' judgment
27	*kebele*-administrators-move-maintenance-threshold	8	0 - 10	Score above which *Kebele* administrators move to already developed micro-watershed during maintenance participation.	Authors' judgment
28	maintenance-threshold	9	5 - 10	Score above which farmers decide to maintain SWC structures.	Calibration
29	demolition-threshold	3	0 - 5	Score below which farmers decide to demolish SWC structures.	RPG (Assefa et al. 2021b)
30	min-members-commitment-threshold	3	0 – 5	Level of commitment of members of micro-watershed associations below which campaign and maintenance participations is relatively lower.	Authors' judgment
31	max-members-commitment-threshold	8	5 – 10	Level of commitment of members of micro-watershed associations above which campaign and maintenance participations is relatively higher.	Authors' judgment
32	min-social-relation-threshold	3	0 – 5	Level of social relation below which commitment of members of micro-watershed associations is relatively lower.	Authors' judgment
33	max-social-relation-threshold	8	5 – 10	Level of social relation above which commitment of members of micro-watershed associations is relatively higher.	Authors' judgment
34	chance-measure-campaign	90	50 – 100	Probability that *Kebele* administrators take measures during campaign participation.	RPG (Assefa et al. 2021b)
35	chance-measure-maintenance	80	50 – 100	Probability that *Kebele* administrators take measures during maintenance participation.	RPG (Assefa et al. 2021b)
36	perception-influence-neighbor-threshold	9	0 - 10	The level of farmers' perception of watershed degradation and future benefits of the program above which he/she directly influences neighbors' campaign participation.	Authors' judgment

*The sum from number 12 to 18 is 1. **Similarly the sum from number 21 to 25 is 1.

The simulation will run for 25 time steps and each time step is equal to one year. This is based on the actual design and implementation of the CBWM program activities, i.e. basic processes of the program are carried out within a year.

3. Process overview and scheduling

This part provides the *setup* and *go* procedures in the model.

3.1. Setup

- *Setup of human agents and their initial locations*
  - Create farmers (member of micro-watershed associations and non-members) randomly distribute to farmlands.
  - Create extension workers and place around the center of the physical environment
  - Create *Kebele* administrators and place around the center of the physical environment

- *Setup of physical environment*

Figure 1 shows steps followed to initialize the physical environment of the model.

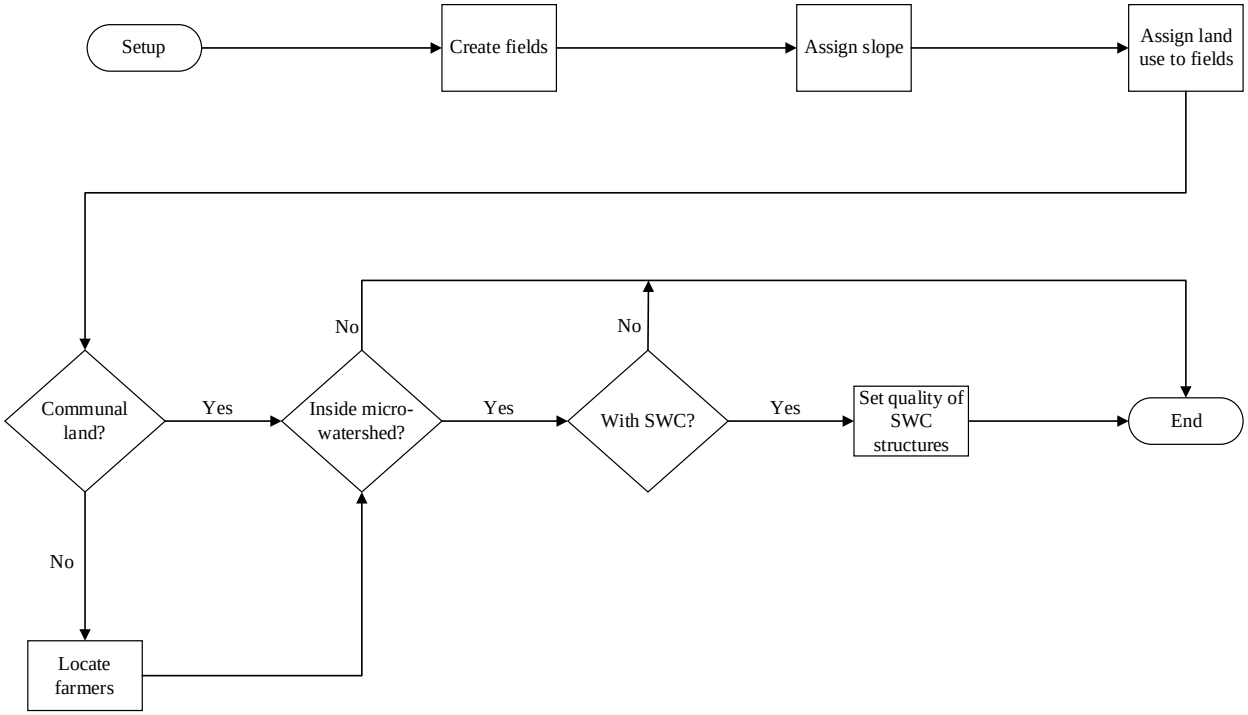

Figure 1: Flowchart of setup of physical environment

- *Create fields*: The physical environment is made up of fields (each 0.25 ha).
- *Assign slope*: The topography of the landscape is diffused from highest slope to lowest at initialization.
- *Assign land use*: Fields with slope > 30 are considered communal land, while those that are =< 30 are considered farmland.
- *Establish micro-watersheds*: create clusters of fields to make micro-watersheds. The initial micro-watersheds are created considering their actual number and land uses in each *Kebele*.
- *Assign area of land covered with SWC structures*: Initialize area of land covered with SWC structures based on actual data collected from the *Kebeles*.

- *Set quality of SWC structures*: The initial quality of SWC structures (2015/16) is an average of 100 runs set in the calibration process, i.e. between 2011/12 and 2015/16. The model was initiated in 2011/12 and average *quality-SWC* in 2015/16 is taken as initial quality of SWC structures for scenario analysis.

3.2. Go procedure

The model has three key processes: (1) selection of new micro-watersheds to be developed, (2) construction of SWC structures through campaign works, and (3) maintenance decisions, where agents interact based on their roles and responsibilities.

Selection of new micro-watersheds to be developed: Every time step or year, the agents meet to select a new micro-watershed (Figure 2). The movement of farmers to the meeting center and their selection of technically viable (higher slope) fields depends on their *perception-watershed*. The movement of extension workers and *Kebele* administrator to the meeting center depends on their commitment. The main objective of extension workers is to improve the farmers' *perception-watershed* of the program so that they first select fields upstream (with steeper slopes). But the influence of extension workers depends on their commitment (*commitment-of-extension-workers*). The *Kebele* administrator also aims to ensure the selection of fields upstream, before proceeding to the lower areas. Depending on his/her commitment *(commitment-of-kebele-administrator*), he/she has the authority to enforce the selection of particular fields.

Construction of SWC structures through campaign works: During campaign works, the agents are expected to move to the newly selected micro-watershed to exert their responsibilities. Farmers whose *campaign-participation* is greater than zero randomly occupy fields in the selected micro-watershed to build SWC structures (Figure 2). They make decisions to participate in campaign works either due to their own attributes or by copying the decision of their neighbor with highest *perception-watershed* of the program. The extension workers randomly move in the selected micro-watershed to ensure the quality of SWC structures. At this stage, the *Kebele* administrator has dual roles: (1) take measures based on farmers' level of participation (campaign-participation), and (2) establish a new association when the micro-watershed is on communal land.

Maintenance decisions: Based on their attributes, farmers could either decide to "maintain" (maintenance-participation >= 8), "ignore" (3 < maintenance-participation < 8) or "demolish" (maintenance-participation =< 3) SWC structures (Figure 2). Farmers whose maintenance decision is "maintain" or "demolish" randomly move to the micro-watersheds to repair and remove the structures respectively. A farmer whose maintenance decision is "ignore" doesn't move. Ignored SWC structures decay overtime. At this stage, the extension workers and *Kebele* administrator randomly move across all micro-watersheds to ensure maintenance quality of SWC structures and to take measures based on farmers' decisions (maintenance-participation) respectively. The movement of both extension workers and *Kebele* administrators depends on their commitment.

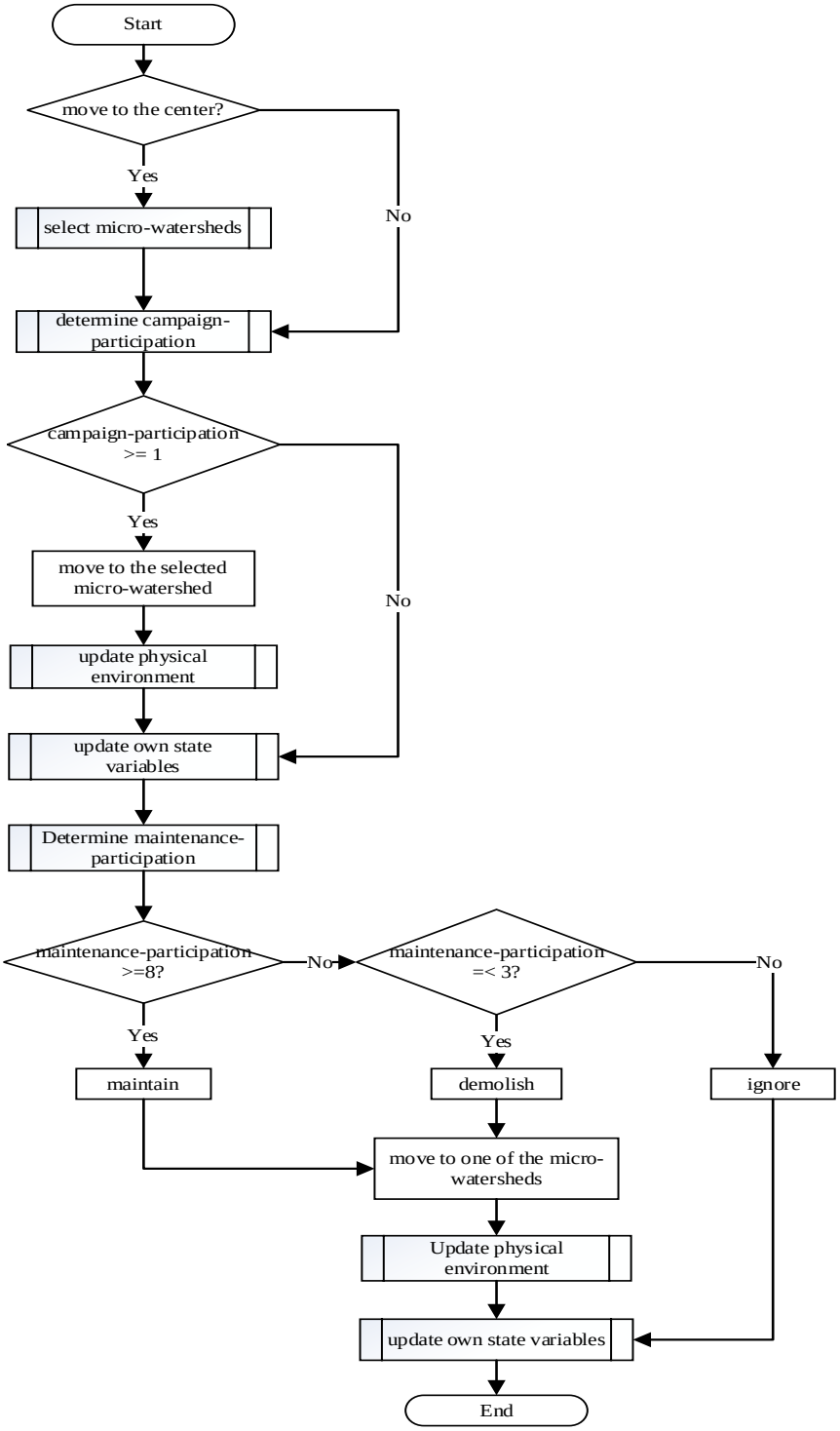

Figure 2: Flowchart of farmers' decision-making behavior in the model.

4. Design concepts

4.1. Basic principles

This model simulates the CBWM program of Ethiopia to explore conditions that enhance coverage and quality of SWC structures. It shows how enhancing farmers' awareness and motivation, establishing and strengthening micro-watershed associations, introducing alternative livelihood opportunities, and enhancing the commitment of local government actors affect area of land covered and quality of SWC structures. Though crucial, similar model

is lacking in the available literature. The model is developed from scratch using empirical data collected from three *Kebeles* that vary in terms of their performance in the CBWM program. This paves the way to develop a middle range model in its level of abstraction. Such models can easily be used to simulate the CBWM program and other similar collective watershed management in other similar localities.

4.2. Emergence

The model has two outcomes: (1) area of land covered with SWC structures and (2) quality of the SWC structures.

4.3. Adaptation

In addition to their own attributes, the decision of farmers to participate in campaign works is directly influenced by the decision of neighboring farmer with higher *perception-watershed*. Farmers also consider commitment and presence (nearness) of *Kebele* administrators and extension workers in their decision. More importantly, dynamic state variables of farmers are updated based on their decisions, which affect subsequent decisions.

4.4. Objectives

Farmers are the most important agent in this model. They have individual objectives of maximizing income and social capital as well as collective objectives of participating in the CBWM program by selecting new micro-watersheds, construct SWC structures during campaign works, and maintaining the constructed structures. As shown in sub-section 3.2, *Kebele* administrators seek the selection of higher slope fields first as well as farmers' higher campaign-participation and maintenance-participation. Similarly, extension workers aim at ensuring the selection of higher slope fields and quality construction of SWC structures.

4.5. Sensing

Farmers sense their attributes to make decisions. They also sense perception-watershed of neighbors with highest score to copy their campaign-participation. Farmers are designed to sense all attributes of fields to make decisions: owners of the field, slope, land-use, micro-watersheds, fields with SWC structures, quality of the SWC structures, and micro-watershed name. They also sense the current commitment-of-*kebele*-administrator, previous measure taken against them due to their decision, and presence of extension workers in their vicinity.

4.6. Interaction

The decision of farmers is influenced by their own attributes and physical environment as well as influences of *Kebele* administrator and extension workers. There is unidirectional (extension workers and farmers, *Kebele* administrator and farmers) and reflexive (interaction among farmers) relationships among agents. The relationship between farmers and fields is bidirectional.

4.7. Stochasticity

At each time step, the model setup uses random seed to generate unique numbers at initialization. As empirically-based model, the values of most state variables were assigned to farmers randomly based on normal distributions with mean and standard deviations. Similarly, most state variables of the fields were randomly assigned based

on data collected from the *Kebeles*. In addition, some system parameters are either drawn from empirical probability distributions or set based on calibration processes.

4.8. Observation

The NetLogo interface shows the physical environment and agents. In addition, plots are used to visualize area of land covered and quality of SWC structures overtime.

5. Initialization

The interference of the model has three *Kebeles* (case studies). One can easily select case study name to initialize particular *Kebele*. Farmers, extension workers, and *Kebele* administrator as well as physical environment are initialized when the model starts. The initial number of farmers (number-of-farmers) can be adjusted using slider, and randomly distributed to the fields on farmland. *Kebele* administrator and extension workers are placed near to the center, and the values of their state variables can be adjusted using sliders. State variables of farmers and fields can also be easily adjusted from slider.

6. Input data

The model do not have external input.

7. Sub models

7.1. Selection of new micro-watersheds

Figure 3 shows how farmers' make decisions to select new micro-watersheds by interacting with extension workers and *Kebele* administrators.

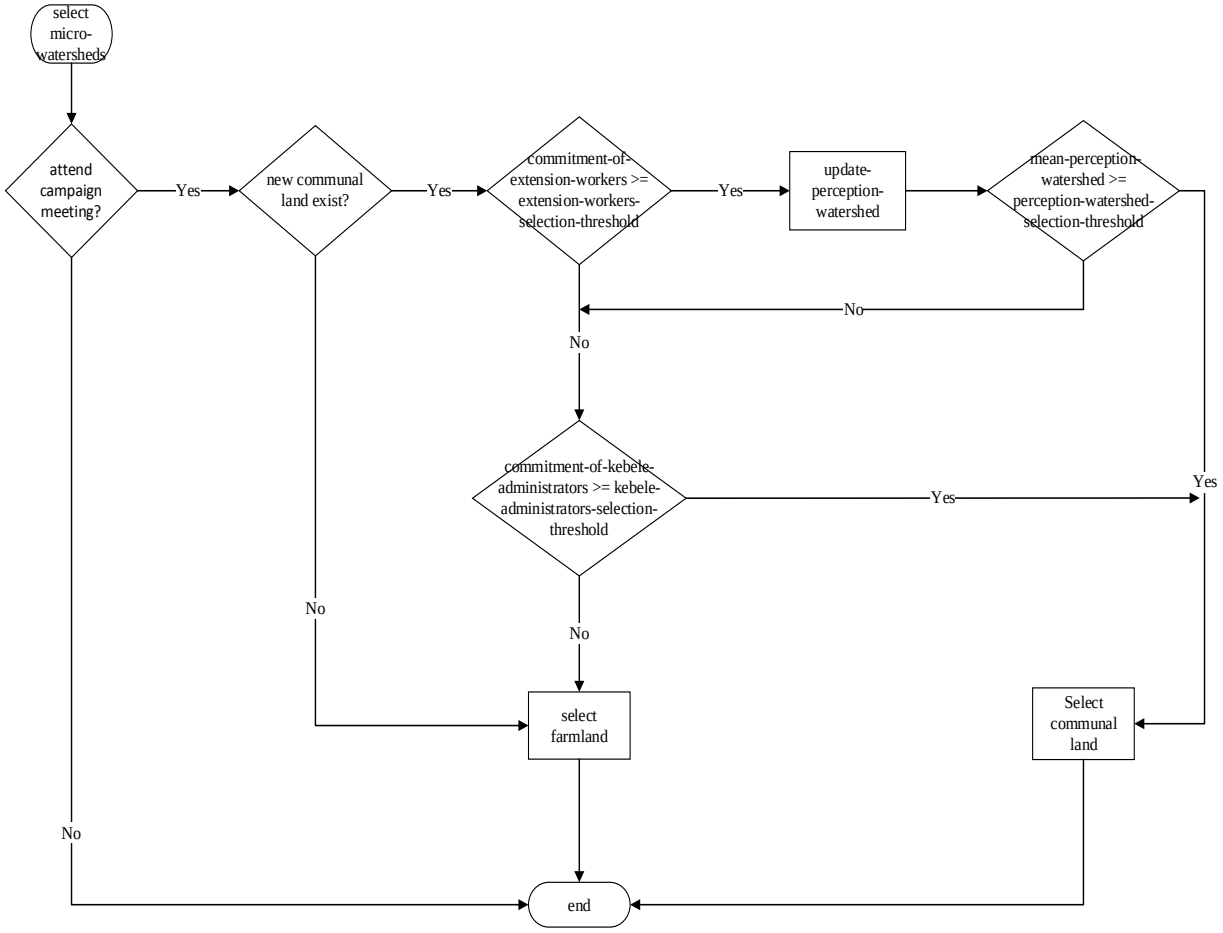

Figure 3 Flowchart of farmers' decision-making during the selection of new micro-watersheds.

- At each time step, farmers, extension workers, and *Kebele* administrator meet to select new micro-watersheds from either communal land or farmland. Farmers are expected to select micro-watersheds on communal land, before proceeding to farmland.
- Extension workers influence perception-watershed. However, the influence of the extension workers depends on their commitment (commitment-of-extension-workers). If commitment-of-extension-workers >= extension-workers-selection-threshold, the extension workers enhances farmers' perception-watershed. If mean-perception-watershed >= perception-watershed-selection-threshold, farmers will select communal land. This means extension workers aware farmers so that they select technically viable fields for campaign workers.
- However, *Kebele* administrator directly influences the decision of farmers, which again depends on his/her commitment (commitment-of-*kebele*-administrator). If commitment-of-*kebele*-administrator >= *kebele*-administrators-selection-threshold, *Kebele* administrators will directly force farmers to select fields considered viable for campaign works at this time in point.

7.2. Determine campaign-participation (Pc):

Farmer's participation in campaign works is the result of two key factors: (1) effect of farmers own attributes and (2) effect of decision of neighbors. The first key factor includes seven factors that influence farmer's participation in campaign works, i.e. campaign-participation (Pc), which is given as:

Pc = perceived-performance-*kebele*-administrator * w-perceived-performance-*kebele*-administrator-campaign + (10 - extent-off-farm-participation) * w-off-farm-participation-campaign + (10 - distance-micro-watershed-campaign) * w-distance-watershed-campaign + education * w-education-campaign + degree-participation-local-organizations * w-degree-participation-local-organizations-campaign + social-capital * w-social-capital-campaign + perception-watershed * w-perception-watershed-campaign Eq.(1)

Distance-micro-watershed-campaign indicates distance between the farmer's position and the micro-watersheds selected for campaign works at this particular time-step. Pc is higher for members of micro-watershed associations. However, farmers directly copy Pc of a neighbor with highest awareness, i.e. perception-watershed >= 9. Pc of each farmer ranges between 0 and 10. Average Pc is calculated as:

$$\text{Average Pc} = \frac{\sum \text{Pc}}{\text{number-of-farmers}} \quad \text{Eq.(2)}$$

7.3. Update physical environment due to campaign-participation

Area of land covered with SWC structures*:* Calculation of area of land covered with SWC structures was preceded by determination of lengths of SWC constructed through campaign works (lengths-SWC-campaign). Lengths-SWC-campaign = campaign-participation * 0.003. This means a farmer constructs 0.003 km for each campaign-participation score, which is assumed to be 3 work days. The total lengths of SWC structures constructed (total-lengths-SWC-campaign) by the farmers is sum of lengths-SWC-campaign. The area of communal land covered with SWC structures due to campaign works is given as:

$$\text{communal-SWC-cover-campaign} = \frac{0.001 \text{ km} * \text{total-lengths-SWC-campaign} * 100 * 4}{0.15 \text{ ha}} \quad \text{Eq.(3)}$$

Similarly, the area of farmland covered with SWC structures due to campaign works is given as:

$$\text{farmland-SWC-cover-campaign} = \frac{0.001 \text{ km} * \text{total-lengths-SWC-campaign} * 100 * 4}{0.11 \text{ ha}} \quad \text{Eq.(4)}$$

In both Eq.(3) and Eq.(4), 0.001 km is width of SWC structures, 100*4 is to convert km^2 to 0.25 ha, and 0.15 ha and 0.11 ha indicate average recommended SWC structures on communal land and farmland per hectare respectively. The area of land covered due to campaign-participation (i.e. communal-SWC-cover-campaign and farmland-SWC-cover-campaign), updates two state variables of fields: communal-swc-cover? and farmland-swc-cover?.

Quality of SWC structures: The quality of SWC structures that the farmers construct through campaign works depends on the presence of extension workers in their vicinity to give technical support. If extension workers are nearby, the quality-SWC will be 10, if not 9.

7.4. Update dynamic state variables of farmers due to campaign-participation

Perception-watershed and social-capital: Crucial to update farmer's perception-watershed and social-capital is measure taken against this farmer after campaign works. A measure taken by *Kebele* administrator is a function of his/her commitment (commitment-of-*kebele*-administrator), measure taken by *kebele* administrator at previous time step, and farmer's distance-from-average-participation (Pc - average Pc). If commitment-of-*kebele*-administrator >= *kebele*-administrators-move-campaign-threshold; the *Kebele* administrator will randomly move in the selected micro-watershed, take measures against farmers that update perception-watershed and social-capital. However, *Kebele* administrators do not always take measures. There is 90% chance that *Kebele* administrator takes *measures* that influence perception-watershed and social-capital.

Membership-watershed-association: The establishment of new micro-watershed association is dependent on the commitment-of-*kebele*-administrator and when the farmers select and develop micro-watershed on communal land. Hence, if commitment-of-*kebele*-administrator >= *kebele*-administrators-move-campaign-threshold and the new micro-watershed is on communal land; then select some farmers (n-new-members-association) randomly to be a member of new micro-watershed.

Income-campaign: Farmers participate in campaign works without any form of remuneration. Both their campaign-participation (Pc), and punishment have negative effect. Hence, income-campaign is given as:

income-campaign = - (campaign-participation-cost + campaign-punishment-cost) Eq.(5)

$$\text{campaign-participation-cost} = \left(\frac{\text{Pc}}{10}\right) * \text{maximum-participation-cost;10 is maximum Pc} \quad \text{Eq.(6)}$$

$$\text{campaign-punishment-cost} = \text{maximum-punishment} - \left(\frac{\text{Pc}}{10} * \text{maximum-punishment}\right);\text{10 is maximum Pc} \quad \text{Eq.(7)}$$

***Perceived-performance-kebele-administrator*:** After campaign works, farmers evaluate performance of the *Kebele* administrator, by updating their perceived-performance-*kebele*-administrator. Farmers' update their perceived-performance-*kebele*-administrator by assessing commitment-of-*kebele*-administrator and average Pc of farmers.

7.5. Determine maintenance participation (Pm)

Maintenance of SWC structures involves labor contribution, strictly observing rules and regulations, and protecting micro-watersheds from disturbances. In this regard, all farmers make maintenance decisions on the already constructed structures. Farmer's participation in maintenance activities or maintenance-participation (*Pm*) (0-10) is the result of six factors.

Pm = perceived-performance-*kebele*-administrator * w-perceived-performance-*kebele*-administrator-maintenance + (10 - extent-off-farm-participation)* w-off-farm-participation-maintenance + (10 - distance-communal-watershed-maintenance)* w-distance-watershed-maintenance + degree-participation-local-organizations * w-degree-participation-local-organizations-maintenance + perception-watershed * w-perception-watershed-maintenance Eq.(8)

However, maintenance-participation is higher for members of micro-watershed associations. For convenience, Pm of each farmer is converted to three maintenance decisions: maintain (*Pm* >= 8), ignore (3 < *Pm* < 8), and demolish (*Pm* =< 3). The average maintenance-participation of the farmers is given as:

$$\text{Average Pm} = \frac{\sum \text{Pm}}{\text{number-of-farmers}} \qquad \text{Eq.(9)}$$

7.6. Update physical environment due to maintenance-participation

Area of land covered with SWC structures: The area of land covered with SWC structures at the end of each time step is the result of farmers' maintenance decision: "maintain", "ignore", or "demolish". This means maintenance decision update two state variables of fields: communal-swc-cover? and farmland-swc-cover?. Farmers with "maintain" decision contribute labor, strictly observe rules and regulations pertaining to maintenance of SWC structures (e.g. not directly destroying or exposing the structures for destruction), and protecting micro-watersheds from disturbances. However, labor contribution for maintenance of SWC structures on communal land is carried out only by members of micro-watershed associations, i.e. members maintain their own watershed (own-watershed). Farmers first maintain SWC structures with lower quality. Members also ensure area closure or guard micro-watersheds on communal land, but first own-watershed. Nonmembers, on the other hand, are expected to strictly observe rules and regulations pertaining to maintenance of SWC structures and protecting the micro-watersheds from disturbances. In other words, a highly motivated nonmembers also ensure area closure or guard micro-watersheds on communal land. However, each farmer is responsible for the maintenance of SWC structures constructed on his/her farmland (own-farmland). Ignored SWC structures decay overtime. Farmers with demolish decision remove SWC structures from fields, but starts with higher quality. The area of land covered with SWC structures was total number of fields with SWC-quality of at least 1. To determine area of land covered with SWC structures at the end of each time step in ha, the following code was used: count patches with [communal-SWC-cover? = true or farmland-SWC-cover? = true] / 4.

Quality of SWC structures: The quality of SWC structures changes based on the maintenance decision of farmers. Maintenance decision updates quality-SWC. If extension workers are nearby, a farmer with "maintain" decision set quality-SWC at 10, if not 9. The quality of ignored SWC structures decline by 1 every time step. A farmer with "demolish" decision, set quality-SWC 0. To calculate average quality-SWC at each time step, the following code was used: if any? patches with [communal-SWC-cover? = true or farmland-SWC-cover? = true] [plot mean [quality-SWC] of patches with [communal-SWC-cover? = true or farmland-SWC-cover? = true]]

7.7. Update dynamic state variables of farmers due to maintenance-participation

Perception-watershed and social-capital: After maintenance decision, farmer's perception-watershed and social-capital are updated because of measures taken (measures) by *Kebele* administrator. Measures taken (measures) by *Kebele* administrators are functions of their commitment (commitment-of-*kebele*-administrator), measures taken (measures) by *kebele* administrator at previous time step, and distance-from-average-participation, which is given as: Pm – average Pm. If commitment-of-*kebele*-administrator >= *kebele*-administrator-move-maintenance-threshold; the *Kebele* administrator randomly moves throughout all micro-watersheds, take measures that update perception-watershed and social-capital. However, *Kebele* administrators do not always take measures. There is

80% chance that *Kebele* administrator take measures. In addition, confrontation between a farmer whose maintenance decision is "maintain" or ensuring area closure or guard micro-watersheds on communal land, and those with maintenance decision of "demolish" leads to a decline in social-capital of the latter.

***Income**:* At the end of each time step, income is updated. Income is a function of income change due to campaign-participation (income-campaign), income change due to maintenance-participation (income-maintenance), income obtained from structures constructed on communal land as a member of micro-watershed association (income-own-watershed), and income obtained from farmland if SWC is constructed on own-farmland (income-own-farmland). These incomes are dependent on the SWC-quality of the fields. For income-campaign (*see* sub-section 7.4). Income-maintenance is determined based on maintenance decision of farmers. For farmers with maintenance decision "maintain", income-maintenance is given as:

$$\text{income-maintenance} = -\left(\frac{Pm}{10}\right) * \text{maximum-participation-cost;10 is maximum Pm} \quad \text{Eq.(10)}$$

For farmers that were punished by *Keble* administrator, i.e. measure = "punish", income-maintenance is given as:

$$\text{income-maintenance} = \text{maximum-punishment} - (Pm/10 * \text{maximum-punishment});10 \text{ is maximum Pm} \quad \text{Eq.(11)}$$

Off-farm-participation: At the end of each time step, farmer's level of off-farm-participation is updated based on his/her amount of income obtained from SWC structures, i.e. income-own-watershed and income-own-farmland. The more farmers obtain income from SWC structures, the more their participation in off-farm activities decreases.

Commitment-member-micro-watersheds: Farmers who are members of micro-watershed associations update their commitment, i.e. commitment-member-micro-watershed at the end of the time step. The commitment of a farmer is a function of his current perception-watershed, social-capital, and income-own-watershed.

Perceived-performance-kebele-administrator: Farmers update their perception of performance of *Kebele* administrators, i.e. perceived-performance-*kebele*-administrator at the end of each time step. Farmers update their perceived-performance-*kebele*-administrator by assessing commitment-of-*kebele*-administrator and average maintenance-participation of farmers.

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