Description of the stylized land use model with feedbacks

The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006; Grimm et al., 2010).

1. Purpose

The purpose of the presented ABM is to explore how system resilience is affected by external disturbances and internal dynamics by using the stylized model of an agricultural land use system.

2. Entities, state variables, and scales

In the model, agents represent farming households. Agents are characterized by the following state variables (see Table 1).

Table 1. State variables (that can change during a model run) of agents

Variable	Description	Domain
savings	An initial amount of financial resources; it is updated every time step	Initial value (€) is a random value following a normal distribution with mean 2400 and standard deviation 240
fully_active	Whether or not the agent is using all the land parcels for production	True, false
not_fully_active	Whether or not the agent is using only part of the land for production	True, false
forced_out	Whether or not the agent is bankrupted	True, false
area_A	Number of land parcels that are used for land use A	(ha)
area_B	Number of land parcels that are used for land use B	(ha)
area_N	Number of land parcels that are not used for production but left unmanaged	(ha)
p_cost_other_A	Unit production cost of land use A except for transportation; updated every step due to the positive feedback	Initial value (€/㎏) is a random value following a normal distribution with mean 0.5 and standard deviation 0.1
p_cost_other_B	Unit production cost of land use B except for transportation; updated every step due to the positive feedback	Initial value (€/㎏) is a random value following a normal distribution with mean 0.5 and standard deviation 0.1
revenue	Amount of income from agricultural production	Minimum is 0 (€) when the agent is forced out of production
consumption	Amount of payment on labor used	Amount of labor used times unit consumption rate per labor (€)
profit	Revenue minus the sum of consumption and production costs	(€)

Table 2. Parameters (that do not change during a model run) of agents

Parameter	Description	Domain
location	Spatial position in the map of a hypothetical rural landscape	GIS coordinates
area	Number of land parcels	[6;21] ha

	owned by the agent.	
labor	Amount of available labor	Initial value is a random value following a normal distribution with mean 50 and standard deviation 5
my_spatial_neighbors	An agent set of others with whom the social network forms	An agent set of spatial neighbors
unit_consumption	Unit consumption per labor	€ / labor unit
likelihood_to_help	The tendency of the agent to provide help to another one when the agent is able to provide such help, randomly determined by the model between 0 and 1	[0, 1]

Table 3. State variables (that can change during a model run) of the system

Variable	Description	Domain
tot_area_A	Total area used by all agents for producing A	ha
tot_area_B	Total area used by all agents for producing B	ha
tot_area_N	Total area not used by agents	ha
tot_production_A	Total production of crop A	(kg)
tot_production_B	Total production of crop B	(kg)
price_A	Regulated by the negative feedback	(€ / kg)
price_B	Regulated by the negative feedback	(€ / kg)
amout_Dead	Total number of agents forced out of production	
amout_Full	Total number of agents using all their land parcels for production	
amout_Between	Total number of agents using part of land parcels for production	
ave_savings	Average financial resources of agents who are not forced out of production	(€)

Table 4. Model output variables (measured by the end of each model run)

Variable	Description	Domain
result_A	Mean value of tot_area_A over last ten steps	ha
result_B	Mean value of tot_area_B over last ten steps	ha
result_N	Mean value of tot_area_N over last ten steps	ha
result_F	Mean value of amount_Full over last ten steps	
result_P	Mean value of amount_Between over last ten steps	
result_D	Mean value of amout_Dead over last ten steps	
result_S	Mean value of ave_savings over last ten steps	(€)

Table 5. Parameters (that do not change during a model run) of the system

Variable	Description	Domain
strength_PEF	Strength level of the negative feedback of price elasticity	[0;66]
strength_ABF	Strength level of the positive feedback of agglomeration benefits	[0;84]
required_labor_A	Labor required per hectare for land use A	labor / ha
required_labor_B	Labor required per hectare for land use B	labor / ha
p_cost_transportation_A	Transportation cost for crop A	(€ / kg)
p_cost_transportation_B	Transportation cost for crop B	(€ / kg)
when_shock	The time step(s) when a shock takes place, randomly determined by the model	[0, 100]
fixed_price_A	Fixed price for crop A when there is no price feedback	(€ / kg)
fixed_price_B	Fixed price for crop B when there is no price	(€ / kg)

feedback

A time step of the model represents one year. Each model run contains 100 time steps.

3. Process overview and scheduling

[Initialization] For one model run, the system is initialized as follows: a virtual landscape of agricultural land use with an area of 10506 hectares (10.2 km * 10.3 km) divided by 676 (26 by 26) farms is generated from GIS and imported to Netlogo, in which one patch represents 1 hectare with a 100-meter resolution. A total number of 676 agents are generated and each is randomly assigned to one farm; farm area varies from 6 hectares to 21 hectares, with an average of 15.5 hectares. Their savings, amount of labor, initial productions costs are randomly assigned following normal distributions as specified in Table 1 and 2. Each agent is linked to his/her nearest five other agents to form a local social network. Each agent starts with half of their land parcels used for A, and half used for B, after the initialization land use activities are determined by the decision-making processes of each agent.

[Procedures in a model run] Each time step starts with agents harvesting crops from previous step, and then they implement of their land use activities decided at the end of previous step; for the harvested crops, the market determines the prices at which they can be sold, then agents sell the produced crops at the market prices (system level properties), which are either fixed (with there is no price feedback) or updated due to the Price Elasticity Feedback; then agents use the income to pay for their consumptions and production costs, after which agents' savings are updated; for the financially unviable farmers, they ask for help within their social network, for an amount of financial resources that would allow them to fully operate on their farms, but a transfer of financial resources only takes place when there is one agent who can and is willing to provide the help; then the system determines if agents' production costs of land use activities are modified, due to agglomeration benefits; there can be shock in the loss of yields happened for this step, which is randomly determined in the beginning of the model run. If a shock takes place, crop yields in the current step are reduced by 80%, which return to the original level in the next time step; by the end of the step, agents decide how they use their land for production in the next time step, those who can still produce crops by using all their land are labelled as "fully active farmers", and those who can operate on part of their land are labelled as "partially active farmers", and those who cannot use their land for production are labelled as "bankrupted farmers"; global variables that reflect the function of the system are updated.

The pseudocode of the main simulation cycle is as follows. Sub-models (capitalized) are further explained in section 6.

```
Initialization {
        Import landscape
        Create agents and assign them to farms
        Assign agent attributes (labor, production costs, savings, likelihood to help)
        Construct social network (nearest 5 agents)
        Initialize system attributes (indicators of spatial, social, and economic resilience)
}

For each time step {
        Agents harvest crops
        Agents carry out land use activities decided in last step
        UPDATE PRICE (Market determines the prices of produced crops)
        UPDATE SAVINGS (Agents receive income by selling crops, pay consumption and
        production costs, update savings)
        If interaction = true,
            SOCIAL INTERACTIONS (Transfer of financial resources between agents)
```

```
UPDATE COSTS (The system modifies production costs)
If shock = true,
    Implement shocks on crop yields

DETERMINE LAND USE (Agents determine land use activities for next step)
update agent states
update global variables (indicators of spatial, social, and economic resilience)
}
```

4. Design concepts

Theory

We built a stylized model which considered some key elements of a land use system. These elements are – to our best knowledge - the following:

- Land use is a spatial variable (Ricardo, 1817; Veldkamp & Lambin, 2001; von Thünen et al., 1966);
- Land use is an economic activity, and so the decisions are driven – to at least some extent – by profit optimization mechanisms (Ricardo, 1817);
- Land uses compete for scarce resources, such as land, labor, and other inputs (Ricardo, 1817);
- Decisions are constrained by factors such as potential yields, production costs, and labor supply (Lambin et al., 2000; Simon, 1957);
- Land users are heterogeneous in terms of personal preferences, economic leeway, demographic properties, etc., which affects their decisions; (Parker et al., 2003; Valbuena et al., 2008)
- Land use decisions are affected by past decisions (e.g. tradition, sunk costs, lock-in, pathway)(Brown et al., 2005; Ellis et al., 2013);
- Land use has an effect on the factors that determine its profitability (e.g. soil quality, crop price, climate, policies, production costs) (Foley et al., 2005; Kalnay & Cai, 2003; Lambin & Meyfroidt, 2011; Matson et al., 1997; Tilman et al., 2001; Turner et al., 2007);
- Land users are social beings who share information, social norms, and common resources (Conley & Udry, 2001; Manson et al., 2016; Rogers, 1962);
- Social Network Theory (Wasserman & Faust, 1994) is applied to connect agents with each other on a basis of spatial proximity. Within the social network, agents value their ties and help each other when difficulties arise.

Emergence

Individual land use activities result from the maximizing strategy constrained by the amount of land, labor, and financial resources of each agent, taking into account of the prices (system property regulated by the negative feedback of price elasticity) and production costs (agent property regulated by the positive feedback of agglomeration benefits). These individual land use activities together result in new prices and changes in productions costs at the system level, which result in changes in individual land use activities.

Adaptation

Reactive adaptations can be found in the behaviors of agents. At each time step, agent reorganize their land use activities by considering the updated prices, production costs, financial resources (savings), etc. When their financial resources are depleting due to losses, they ask for help within their social network to avoid being forced out.

Objectives

Agents have the goal to maximize their profits from land use activities. Besides, altruistic agents have the objective to maintain the integrity of their rural community (represented by their social network) by providing help to those in need.

Learning

Learning is not considered in this model version.

Prediction

Agents only react to changes and do not predict the future.

Sensing

Agents perceive the changes in prices, production costs, and use the information to make land use decisions for the next time step.

Interaction

There are direct and indirect interactions between agents. The direct interactions are through the social network: when agents suffer from financial losses and cannot continue with farming, they ask within their social network for help, and those with more financial resources can provide help. Through interactions, the integrity of the rural community is preserved — agents are willing to provide help because they value their ties and the community. The indirect interactions are through the feedbacks: as individual behaviors together modify system level properties (total amount of production, and agglomeration of economic activity), they in return affect the decision of each individual (through prices and production costs).

Stochasticity

Randomness existed in various occasions in this model: 1) the agents created in Netlogo are randomly assigned to their farms with different sizes in the landscape, which is imported from a GIS files; 2) agents' attributes are randomly determined to form normal distributions; 3) the sequence that agents are called to perform the tasks as described in section 3 is controlled by a random seed, which defers per model run; 4) the time step when a shock takes place is randomly determined by each model run.

Collectives

In this model each agent has a social network based on spatial proximity. Social interactions only take place within one's network.

Observation

We observe the system behavior in three categories so that the core functions we considered for the system is monitored—total amount of land being used for producing different crops (A or B) or left idle, rural community composition (number of fully active farmers, partially active farmers and bankrupted farmers), and average accumulated financial resources. When model results were compared across different model runs, these variables are summarized by the each of each model run, taking the mean value over the last ten time steps.

5. Initialization

For one model run, the system is initialized as follows: a virtual landscape of agricultural land use with an area of 10506 hectares (10.2 km * 10.3 km) divided by 676 (26 by 26) farms is generated from GIS and imported to Netlogo, in which one patch represents 1 hectare with a 100-meter resolution. A total number of 676 agents are generated and each is randomly assigned to one farm; farm area varies from 6 hectares to 21 hectares, with an average of 15.5 hectares. Their savings, amount of labor, initial productions costs are randomly assigned following normal distributions as specified in Table 1 and 2. Each agent is linked to his/her nearest five other agents to form a local social network. Each agent starts with half of their land parcels used for A, and half used for B, after the initialization land use activities are determined by the decision-making processes of each agent.

6. Submodels

Update prices

For the whole system:

$$price\_A_{(t)} = -1 \times (0.08 + strength\_PEF^{1} \times 0.01) \times 10^{-5} \times tot\_production\_A_{(t)} + 3.1 + 0.0125 \times strength\_PEF \quad (1)$$

$$price\_B_{(t)} = -1 \times (0.08 + strength\_PEF \times 0.01) \times 10^{-5} \times tot\_production\_B_{(t)} + 3.1 + 0.0125 \times strength\_PEF \quad (2)$$

This submodel serves to form the Price Elasticity Feedback (PEF), as individual land use activities together determine the total amount of production for each crop from their activities from previous step, the market determines new prices given the current productions. These prices are used by individual agents at this time step to determine land use activities for the next time step in the submodel of determine land use below.

Update savings

For each agent:

$$production\_A_{(t)} = area\_A_{(t)} \times unit\_production\_A_{(t)} \quad (3)$$

$$production\_B_{(t)} = area\_B_{(t)} \times unit\_production\_B_{(t)} \quad (4)$$

$$profit\_A_{(t)} = production\_A_{(t)} \times (price\_A_{(t)} - p\_cost\_other\_A_{(t-1)} - p\_cost\_transportation\_A_{(t-1)}) \quad (5)$$

$$profit\_B_{(t)} = production\_B_{(t)} \times (price\_B_{(t)} - p\_cost\_other\_B_{(t-1)} - p\_cost\_transportation\_B_{(t-1)}) \quad (6)$$

$$consumption_{(t)} = (area\_A_{(t)} \times required\_labor\_A + area\_B_{(t)} \times required\_labor\_B) \times unit\_consumption \quad (7)$$

$$savings_{(t)} = savings_{(t-1)} + profit\_A_{(t)} + profit\_B_{(t)} - consumption_{(t)} \quad (8)$$

Update costs

For each agent:

$$p\_cost\_other\_A_{(t)} = p\_cost\_other\_A_{(t-1)} - (tot\_area\_A_{(t)} - tot\_area\_A_{(t-1)}) \times (0.16 + strength\_ABF^{2} \times 0.01) / tot\_area \quad (9)$$

$$p\_cost\_other\_B_{(t)} = p\_cost\_other\_B_{(t-1)} - (tot\_area\_B_{(t)} - tot\_area\_B_{(t-1)}) \times (0.16 + strength\_ABF \times 0.01) / tot\_area \quad (10)$$

This submodel serves to form the Agglomeration Benefits Feedback (ABF), as individual land use activities together determine the change on the total area used for one crop, the system determines how much benefits can be reduced on individuals' production costs for producing that crop. The modified production costs are used by individual agents at this time step to determine land use activities for the next time step in the submodel of determine land use below.

Social interactions

When social interaction is true, agents with financial difficulties can ask within their social network for help. Due to financial losses, some agents become partially active as they can only operate on part of their land parcels or even currently bankrupted. These agents turn to the agent in their network with the largest amount of financial resources. They ask for an amount that can allow them to return to a fully active state. This amount is calculated based on the area of their idle land and the current production

[1] In the model exploration, we distinguish situations where PEF is low, medium, or high. These strength levels refer to a strength_PEF at 5, 20, 35 respectively.

[2] In the model exploration, we distinguish situations where ABF is low, medium, or high. These strength levels refer to a strength_ABF at 6, 25, 44 respectively.

costs. The transfer of financial resources is made when the agent being asked is able to transfer this amount after paying his/her own consumption. After each transfer, financial resources of both the asking and the asked agents are updated.

In the model exploration, we distinguish three situations for this mechanism — selfish agents, heterogeneous interaction, and altruistic agents. For selfish agents, there is no social interaction as agents are not willing to provide help; for heterogeneous interaction, the probability of one agent to provide help (when he/she is able to) depends on a parameter of this agent, which is randomly determined in a model run. For altruistic agents, agents are all willing to help when they are able to.

Shocks

In the model exploration, when shocks are true, the time step when a shock is implemented is randomly determined by the model run in the initialization phase. At that time step, the yields of crops are reduced by 80%, and return to the original value in the next time step. For a model run that has multiple shocks, we implement them as 3-in-a-row shocks, in which another shock takes place after the previous shock is just recovered.

Determine land use

For the active agents (fully actively or partially active), given the current prices and production costs, they reorganize their land use activities for the next time step by assigning their farmland (per hectare) for either land use A or B, in the way that their potential profits can be maximized. The optimal is found with the following constraints: the way that each hectare of land is used for either A or B or set aside, does not require an amount if labor that is larger than what the agent has; the agent has enough financial resources to carry out the production.

For each active agent (forced_out is false):

$$\text{area\_A}_{(t+1)} \times \text{required\_labor\_A} + \text{area\_B}_{(t+1)} \times \text{required\_labor\_B} <= \text{labor} \tag{11}$$

$$\text{area\_A}_{(t+1)} \times \text{unit\_production\_A} \times (\text{p\_cost\_other\_A}_{(t)} + \text{p\_cost\_transportation\_A}_{(t)}) + \text{area\_B}_{(t+1)} \times \text{unit\_production\_B} \times (\text{p\_cost\_other\_B}_{(t)} + \text{p\_cost\_transportation\_B}_{(t)}) <= \text{savings}_{(t)} \tag{12}$$

$$\text{area\_A}_{(t+1)} + \text{area\_B}_{(t+1)} <= \text{area} \tag{13}$$

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