Supplementary Material

Modelling agricultural innovations as a social-ecological phenomenon

A: AG-Innovation Model ODD Protocol

1. Overview

Following the Overview, Design concepts and Details (ODD) model description framework (Grimm et al., 2006), this section describes the purpose, entities, state variables, scales, design concepts, model input data, and submodels within the AG-INNOVATION ABM.

2. Model purpose

The goal of the Ag-Innovation agent-based model is to explore and compare the effects of two alternative mechanisms of innovation development and diffusion (exogenous, linear and endogenous, non-linear) on emergent properties of food and income distribution and adoption rates of different innovations. The model also assesses the range of conditions under which these two alternative mechanisms would be effective in improving food security and income inequality outcomes**.** Our modelling questions were: i) How do cross-scalar social-ecological interactions within agricultural innovation systems affect system outcomes of food security and income inequality? ii) Do foreign aid-driven exogenous innovation perpetuate income inequality and food insecurity and if so, under which conditions? iii) Do community-driven endogenous innovations improve food security and income inequality and if so, under which conditions? The Ag-Innovation model is intended to serve as a thinking tool for the development and testing of hypotheses, generating an understanding of the behavior of agricultural innovation systems, and identifying conditions under which alternated innovation mechanisms would improve food security and income inequality outcomes.

3. Entities, state variables, and scales

The Ag-Innovation model consists of three key agents: producers, collectives, and innovators. Collectives represent farmers' associations or groups in farmer field schools who collectively test and experiment with innovations that may be suitable. The innovators represent external agricultural agencies such as international agricultural development organizations or private agencies that are funded by external or foreign aid. In the endogenous mechanism of innovation, innovator agents are collectives who are directly connected with early adopters (small and medium producers) for innovation dissemination. Late adopters (large producers) interact with early producers to spread innovation adoption**.** In the exogenous mechanism of innovation, innovator agents are external innovators who are directly connected with early adopters (in this case, large producers) for innovation dissemination. Late adopters (small and medium producers) interact with early producers for the spread of innovation adoption. The producers and innovators agents have attributes which are outlined in Table S1.

Table S1: State variables for the agents in Ag-Innovation model

Attribute	*Description*	*Type*	*Unit/Dimensions*	*Values*
Producers				
landsize	Size of farmland	static	Hectares (ha)	Range 1- 30
farmtype	Type of farmer	static	-	(Small, medium, large)
soilfertility	Index that represents soil fertility	dynamic	-	Range 1-100
householdsize	Number of members in the household	static	-	Range 3-17
adoptertype	Type of adopter	static	-	(Early adopter, late adopter)

capital	Capital owned (variable representing capital)	dynamic	-	Range 1-1000
cropchoice	Choice of crop for production	dynamic	-	(Rice, wheat, maize or millet)
cropproduction	Amount of crop produced	dynamic	Kilogram	
food-requirement	Amount of food required by the agent's household in a year	dynamic	Kilogram	
food-secure	Binary variable if crop production is higher than food requirement, or if crop production is lower than food requirement	dynamic	-	(True orFalse)
innovation-needed	Binary variable	dynamic	-	(True or false)
innovation-desire	Type of innovation needed by agent (production, stability or conservation)	dynamic	-	
adoption-capacity	Capacity of agent to adopt innovation	static	-	(range 0-1 based on farm type)
innovation-adopted	Type of innovation adopted	dynamic	-	(production, stability, conservation)
adoption-status	Binary variable, whether the agent adopted an innovation or not	dynamic	-	(True or False)
Innovators				
innovator-type	Type of innovator); changes with innovation mechanism (endogenous or exogenous)	static	-	(External innovator or collective)
innovation-capital	Capital endowment of innovator	dynamic		range 0-10000
innovation-goal	Type of innovation that the innovator wants to develop	dynamic	-	(Production, stability, or conservation)
innovation-available	Type of innovation developed by the innovator	dynamic	-	(Production, stability or conservation)
knowledge-efficiency	Index that represents knowledge of what kind of innovation is needed by producers (perceived innovation desire/actual innovation desire of producers)	dynamic	-	Range 0-1
capital-efficiency	Index that represents capital as proxy for infrastructure development (capital available / capital needed)	dynamic	-	Range 0-1

4. Process overview and scheduling

Mechanisms of innovation (endogenous and exogenous):
Producers perform nine actions: *i)* assess climate risk, *ii)* make crop choice for cultivation, *iii)* estimate expected crop production, *iv)* assess in-novation need *v)* develop innovation desire, *vi)* adopt innovation (directly from innovator/ collective agents by early adopters and social learning for late adopters), *vii)* assess crop production, *viii)* allocate produce for household consumption and selling and *ix)* allocate a share of available capital to collectives. The innovator agents perform four actions: *i)* update capital for innovation, *ii)* set innovation goal, *iii)* develop innovation, and *iv)* disseminate innovation to early adopters.

In endogenous mechanism, collective innovators update innovator capital based on the pooling of capital allocated by producers connected within their network. In the exogenous mechanism, external innovators update innovator capital based on capital allocated through foreign aid capital. In the endogenous mechanism, the goal for innovation development (innovation-goal) of the collective innovator is the type of innovation (production, stability, conservation) desired by the largest number of producers linked to the network. In the exogenous mechanism, the goal for innovation development (innovation-goal) of the external innovator is decided randomly between production, stability, and conservation at each time step.

The model simulates climate patterns at the macro-scale through changes in temperature and precipitation at the various phases in crop growth cycle (sowing, growing and maturing phases). These climate variables influence crop selection decisions of producer agents and determine crop yield. Crop yield is also influenced by type of innovation adopted as well as the capacity of the innovation (efficacy) to influence crop yield.

The key outcome variables in the model are food security, income inequality, and adoption rates of different types of innovations (production, stability, and conservation) over time. We ran the model over 200 times, each run with 100-time steps. Each time step represents an agricultural production year.

Table S2: Update of state variables at each time step.

State variables	Updates & Scheduling
Climate zone	Remains constant
Adopter type	Constant (for both mechanisms)
Soil fertility	Dynamic, based on type of innovation adopted
Climate risk assessment	Dynamic, based on a dynamic memory of temperature and precipitation. Patches calculate the difference between temperature and precipitation (sowing, growing and maturing) values at time step with the mean temperature and precipitation (sowing, growing and maturing) for past 10 time- steps. The difference from mean is used to estimate climate risk at a particular time step.
Crop choice	Dynamic, based on climate risk assessment
Land size	Remains constant
Farm type	Remains constant
Household size	Remains constant
Capital	Dynamic, based on income received from selling surplus crop and capital donated to collective for innovation development
Innovation belief	Dynamic, based on comparison of expected crop production with past crop production history
Innovation desire	Dynamic, based on assessment of soil fertility, production gap and production variability from past crop production history
Innovation adopted	Dynamic, based on innovation need and availability (early adopters) and influence of
Innovation yield	Dynamic, based on innovation adopted and crop yield at time step
Adoption status	Dynamic, binary (1 -adopted, 0- Not adopted)
Adoption capacity	Dynamic, based on capital of the producers
Food requirement	Remains constant
Producer allocated capital	Dynamic, based on capital available
Innovation goal	Dynamic, based on most popular innovation desire of producers or random
Capital	Dynamic, based on the sum of all capital allocated by linked producers (endogenous) and aid allocated during climate event (exogenous)
Innovation development efficiency	Remains constant
Innovation capacity	Dynamic, based on capital available
Capital allocation rate	Remains constant

5. Design concepts

Basic principles:

Our modeling approach was to develop an empirically based but stylized model of innovation that captured aspects such as spatial arrangements, heterogeneity of actors, and interactions within the social-ecological system while also allowing for exploration of the different alternate mechanisms and network structures that influenced innovation outcomes. The development of the Ag-Innovation model was an iterative process of drawing from theory and empirical evidence to construct a model that adequately represented the social-ecological interactions within alternate mechanisms of innovation. The empirically based but stylized model was a mechanism based stylized model with a sufficient level of empirical detail that generated outcomes comparable to real-world observations.

Emergence:
The key outcomes of the model are food security, income inequality and adoption rates of production, stability, and conservation-oriented innovations of the producer agent population. These outcomes emerge from the social and social-ecological interactions between and within producers, innovators and collectives with each other and their environment.

Adaptation:
Producer agents can perceive climate risks and adapt to these risks through alternate crop selection. If climate risk is 'early drought', producers adapt through a crop choice of either sorghum or millet. If climate risk is 'mid-season drought', producers adapt through a crop choice of either maize or millet. If climate risk is 'terminal drought', producers adapt through a crop choice of either maize or millet. If climate risk is 'excess rainfall', producers adapt through a crop choice of either rice or sorghum. If climate risk is 'extreme temperature', producers adapt through a crop choice of sorghum.

External innovator agents from the exogenous mechanisms also perceive climate risks. If there is a climate risk, innovator agents adapt by updating capital from foreign aid allocation.

Learning:
Producer agents learn through a memory of their past production histories. They form innovation desires and beliefs based on the memory of past production histories. The following algorithms illustrate how learning is embedded within actions of producer agents in the model:

> If soil fertility is lower than a certain threshold, the agents set their innovation belief as true and innovation desire as 'conservation'.
> If the agents have a negative production gap between current crop production and mean of past production history, the agents set their innovation belief as true and innovation desire as 'production'.
> If agents have a high standard deviation in crop production history (indicating high crop production variability), agents set their innovation belief as true and innovation desire as 'stability'.

The model implements social learning for innovation adoption diffusion where producer agents with type 'late adopters' learn about the innovations adopted by other early producers in their vicinity and adopt the innovation if the most popular innovation adopted by early adopters matches with their innovation desire.

The model implements social learning for collective innovators as well where collective agents learn about the innovation desires of 'early adopters' linked in a network with them and assess the most popular innovation desire to set their innovation goal.

Prediction:
The model is designed to serve the purpose of mechanism-based exploration of innovations, there is no design component of prediction in the model.

Sensing:
All producer agents are assumed to be able to sense temperature and precipitation in the cropping season. Producers can also perceive climate risks and make crop choices accordingly as well as estimate expected crop production for the season to form innovation belief (is innovation needed?)

Interaction:
Innovators- Producers:

> Innovators interact with early producers through innovation dissemination for innovation adoption.

Collectives -Producer:

> Collectives interact with producers in the network to form innovation goals
> Collectives interact with early producers through innovation dissemination for innovation adoption

Producers- Producers:

> Early adopter producers interact with late adopter producers through innovation knowledge sharing

for innovation diffusion.

Producers interact with producers through collective formation and capital pooling for innovation development.

Producers – Farmlands

Based on climate risk perception, producers interact with farmland through crop selection and cultivation.

Producers interact with farmland through the formation of innovation beliefs and desires.

Crop- Soil

Crop interacts with soil through the regulation of soil fertility and crop diversity.

Stochasticity:

Stochasticity is introduced in the model during the initialization of climate variables; temperature and precipitation in sowing, growing and maturing seasons where there is a random variation of temperature and precipitation over time to account for short term climatic variability.

Collectives:

Collectives represent farmers associations or groups in farmer field schools who collectively test and experiment with new innovations that may be suitable. In the endogenous mechanism of innovation, the assessment of innovation goal of collectives is conducted based on a calculation of the most desired innovation goal of the producer agents linked to the collective. Producers interact with collectives through the pooling of a share of their available capital.

Observations:

The model outcomes are food security, income inequality and innovation adoption rates for production, stability and conservation-oriented innovations.

Food security is an outcome that shows the proportion of producer agents who are food secure as compared to the total number of producer agents. A producer agent is food secure if their food production is more than their food requirement.

Income inequality is an outcome that shows the Gini coefficient of capital distribution among producer agents which represents the degree of inequality in a distribution. A Gini coefficient of 0 expresses perfect equality while a Gini coefficient of 1 expresses maximum inequality among values.

Innovation adoption rate is a count of number of producers who adopted the innovation (production, stability or conservation) divided by the total number of producers.

6. Model Initialization

The model environment for the AG-Innovation model represents the entire country divided into four key agroecological zones. These are represented as patches divided into four climate zones with respective attributes of temperature and precipitation, soil fertility and crops grown within which agents reside. The distribution of producer agents within the four climate zones is based on proportion distribution of farmers from empirical data (9% climate zone 1, 17% climate zone 2, 55% climate zone 3 and 18% climate zone 4). The producers have attributes such as farm type, land size crops grown, household size and food requirement that was also derived from empirical data from secondary sources (Table S3).

In the endogenous mechanism of innovation, innovator agents are collectives who are directly connected with early adopters (small and medium producers) for innovation dissemination. Late adopters (large producers) interact with early producers to spread innovation adoption.

In the exogenous mechanism of innovation, innovator agents are external innovators who are directly connected with early adopters (in this case, large producers) for innovation dissemination.

Table S3: Calibration of agent attributes based on empirical data

	Climate zone 1	**Climate zone 2**	**Climate zone 3**	**Climate zone 4**
Sowing temperature	Mean 40 °C SD 2	Mean 36.9 °C SD 2	Mean 33.5 °C SD 2	Mean 31 °C SD 2
Growing temperature	Mean 38 °C SD 2	Mean 34.5 °C SD 2	Mean 30.2 °C SD 2	Mean 30 °C SD 2
Maturing temperature	Mean 36 °C SD 2	Mean 36.3 °C SD 2	Mean 33.2 °C SD 2	Mean 33.9 °C SD 2
Sowing precipitation	Mean 100 mm SD 20	Mean 300 mm SD 50	Mean 600 mm SD 100	Mean 700 mm SD 100
Growing precipitation	Mean 50 mm SD 5	Mean 100 mm SD 25	Mean 180 mm SD 50	Mean 200 mm SD 100
Maturing precipitation	Mean 15 mm SD 5	Mean 20 mm SD 5	Mean 60 mm SD 25	Mean 80 mm SD 30
Soil fertility	Mean 20 SD 10	Mean 40 SD 10	Mean 60 SD 10	Mean 80 SD 10
Farm type	90% small farmers, 10% medium farmers	10% large, 20% medium and 70% small farmers	20% large, 30% medium and 50% small farmers	40% large, 30% medium and 40% large farmers
Crops grown	millet	"millet" "rice",	"sorghum" "millet" "maize"	"sorghum" "millet""maize""rice"
Household size	mean 5 median: 3	mean 8 median 5	mean 12 median 5	mean 12 median 5

Per capita maize consumption	200 kg per year		
Per capita millet consumption	200 kg per year		
Per capita rice consumption	150 kg per pear		
Per capita sorghum consumption	200 kg per year		
Farm type	Large	Medium	Small
Land size	range 10-30 ha	range 5-9 ha	range 1-4 ha
Capital	Range 801-1000	Range 401-800	Range 100-400
Adoption capacity	Range 0.6-0.9	Range 0-3-0.6	Range 0.0- 0.3

7. Model Input Data

The model has no input data.

8. Submodels

Crop yield module

In order to formalize the relationship between temperature and precipitation at sowing, growing and maturing phases and average crop yields of rice, maize, sorghum, and millet crops, we used insights from a previous study of author (Sanga, 2020) that developed a series of multivariate regression analyses using crop yield and climate data from 1961-1990 (FAO, 2017) to functionalize the crop yield in the model. The patches owned by the producer agents in the model calculate crop yield at each patch based on climate variables (temperature and precipitation in sowing, growing and maturing seasons).

$$Yieldmaize = -1440.30 + 285.15 * sowingtemp + 18.73 * sowing\ pr + 212.39 * growingtemp - 0.81 * growing\ pr - 45.39 * maturingtemp + 10.53 * maturingprep$$

$$Yieldsorghum = -4301.93 + 115.89 * sowingtemp + 11.22 * sowing\ pr - 70.97 * growingtemp - 2.30 * growing\ pr + 115.96 * maturingtemp + 7.72 * maturingprep$$

$$Yieldmillet = -5385.86 + 94.11 * sowingtemp + 2.50 * sowing\ pr + 131.21 * growingtemp + 2.09 * growing\ pr - 41.99 * maturingtemp - 0.04 * maturingprep$$

$$Yieldrice = -1941.04 + 93.40 * sowingtemp + 3.77 * sowing\ pr + 38.66 * growingtemp + 0.73 * growing\ pr - 63.48 * maturingtemp + 0.68 * maturingprep$$

Climate risk assessment module

Patches calculate the difference between temperature and precipitation (sowing, growing and maturing) values at time step with the mean temperature and precipitation (sowing, growing and maturing) for past 10 time-steps. The difference from mean is used to estimate climate risk at a particular time step. Agents' perceptions of these climate risks can be changed through a climate switch (on / off).

Climate risk = Early drought if [sowing temp diff > 3; sowing precip diff < 0]
Climate risk = Midseason drought if [growing temp diff > 3; growing precip diff < 0]
Climate risk = Terminal drought if [maturing temp diff > 3; maturing precip diff < 0]
Climate risk = Excessive rainfall if [sowing precip diff > 100 or growing precip diff > 100 or maturing precip diff > 100]
Climate risk = Extreme temperature if [sowing temp diff > 3 or growing temp diff > 3 or maturing temp diff > 3]

Crop selection module

Producer agents choose crops based on climate risk perception. The functionalization of crop choice with climate risk is based on past works of author(Sanga et al., 2021) which assessed agricultural decision-making under climate risk and uncertainty using role playing games. These insights were embedded in the model through algorithms such as:

If climate risk = 'early drought', crop choice [sorghum or millet]
If climate risk = 'mid-season drought', crop choice [maize or millet]
If climate risk = 'terminal drought', crop choice [maize or millet]
If climate risk= 'excess rainfall', crop choice [rice and sorghum]
If climate risk = 'extreme temperature', crop choice [sorghum].

Innovation desire and belief formation module

The model implements the beliefs, desires and intentions architecture to form dynamic innovation beliefs and desires of the producer agent. Belief is based on the state of the agricultural production of the agent and is a state-variable that estimates if the agent needs innovation at a particular time-step. Desires is based on what kind of innovation the agent needs. The agents can choose between three typologies of innovations: 'production', 'stability' and 'conservation'.[1]

Agents estimate soil fertility at their patches, estimated crop production at current time step as well as the mean and standard deviation of past crop production history for prior 10 time-steps.

- If soil fertility is lower than a certain threshold, the agents set their innovation belief as true and innovation desire as 'conservation'.
- If the agents have a negative production gap between current crop production and mean past production history, the agents set their innovation belief as true and innovation desire as 'production'.
- If agents have a high standard deviation in crop production history (indicating high crop production variability), agents set their innovation belief as true and innovation desire as 'stability'.

Innovation adoption module

Early adopters adopt innovation if innovation desire is same as innovation available by linked innovator or collective agent. Agent invests in the innovation, updates their adoption status and updates its adoption production.

Late adopters link with their nearest neighbors of early adopters, if innovation desire is same as innovation

[1] Note that here innovation with 'production' , 'stability' and 'conservation' are representative of a repertoire of innovations such as efficient fertilizers, improved irrigation technologies, pest control and management, soil improvement technologies and system of Rice Intensification (SRI) technique that lead to increase in 'production'; drought resistant seed varieties, early maturing crop varieties, local varieties of millet and sorghum, crop management techniques (change in sowing dates, intercropping, change in crop density, crop rotation) that increase crop production 'stability' and soil and water conservation innovations (soil bunds, compost manure and cover crops) that increase soil 'conservation' [15]. In order to minimize the complexity of the model, these technological innovations are not explicitly modeled in the AG-Innovations model but are represented indirectly through the typologies of yield stability, productivity and conservation

available by linked neighbor, agent invests in the innovation, updates their adoption status and updates its adoption production.

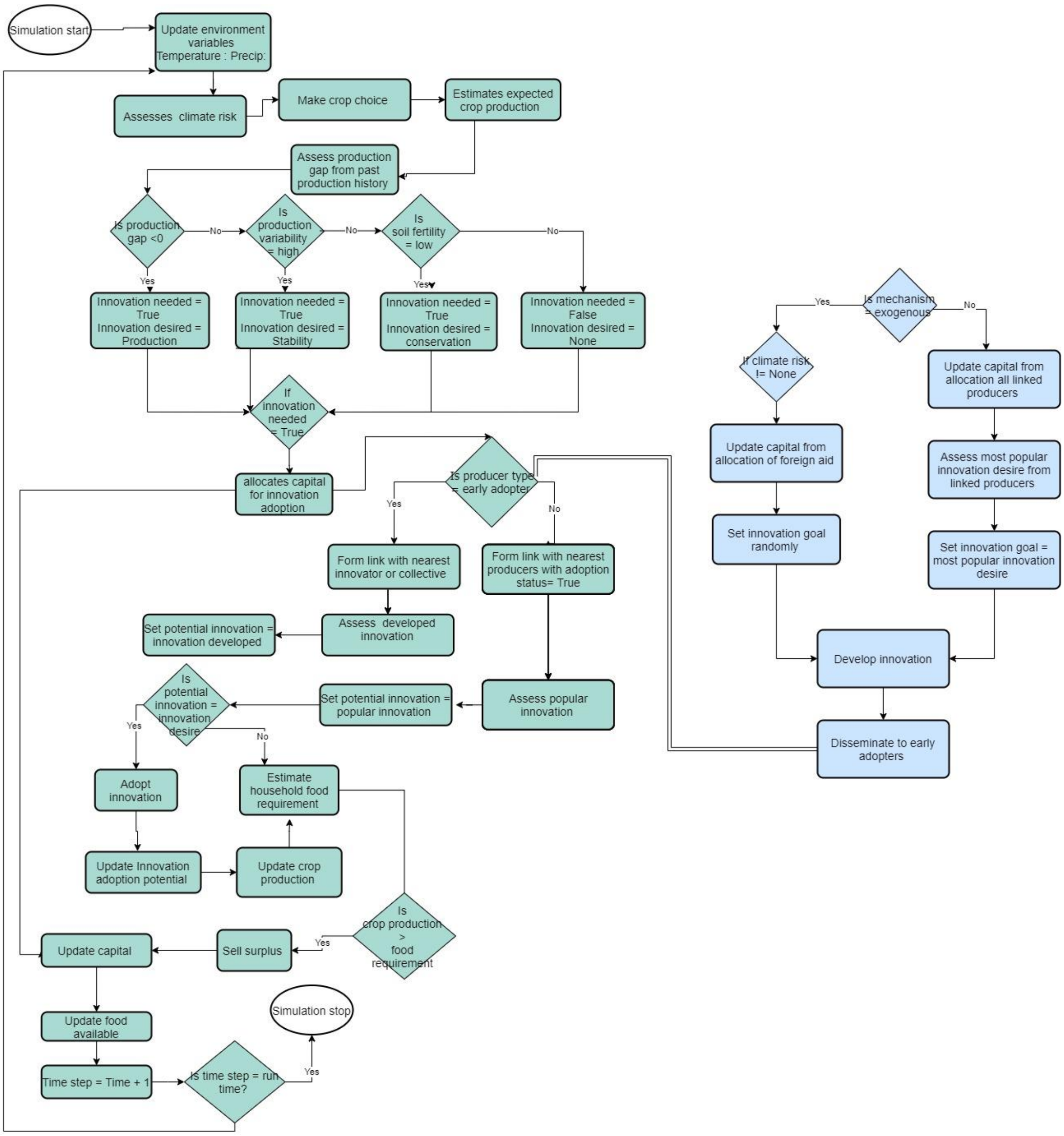
Yield update module

If innovation adopted is ¨production ¨, crop yield increases by an amount proportional to the innovation efficiency and soil fertility decreases. If innovation adopted is ¨conservation ¨, crop yield increases by an amount proportional to the innovation efficiency and soil fertility increases. If innovation adopted is ¨stability¨, crop yield maintains by an amount proportional to the innovation efficiency.

Consumption and selling module

Producer agents calculate household food requirement. If food production is greater than food requirement, agents set their status food secure and sell excess food. Otherwise, agents set status food insecure.

B: Detailed flowchart of the AG- Innovations model



References

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., … DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, *198*(1–2), 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023