Describing the **Vi**ability of the **S**ocial-Ecological **A**groecosystem (ViSA) Spatial Agent-based Model According to the ODD Protocol

1. Introduction

Agent-based modelling (ABM) has been widely applied in social science (Squazzoni 2010) since it has the capability of modelling individual heterogeneity in space (Gilbert 2008) as compared to variable-based approaches using structural equations, system-based approaches using differential equations (Billari et al. 2006, Gilbert 2008) or optimization models using linear programming and optimal behavior of actors (Shaaban et al. 2022). Further, it simulates the evolution of a system of adaptive autonomous interacting agents (Janssen & Ostrom 2006). These advantages gave ABM a good opportunity to invade the simulation of the social-ecological system's interaction at multiple scales (Miyasaka et al. 2017) and more specifically in simulating the change of land use as well as the provision of ecosystem services (ESS) in agricultural landscapes (see Happe et al. (2004), Piorr et al. (2009), Brady et al. (2012), Le et al. (2008), Sun & Müller (2013), Pohle & Zasada (2014), Chen et al. (2014), Habib et al. (2016), Tieskens et al. (2017)).

Building and publishing ABMs without a clear transparent and comprehensive standard description brings a lot of confusions and misunderstandings that usually make it difficult to replicate, assess and compare them or even to be further expanded (Müller et al. 2014). Here, I describe the "Viability of the Social-ecological Agroecosystem (ViSA)" model (Shaaban & Piorr 2021) according to the Overview, Design Concepts and Details (ODD) protocol developed for describing agent-based models in order to facilitate model replication and communication with other scholars. The ODD protocol has been developed by Grimm et al. (2006) and has been updated by Grimm et al. (2010). The underlying concept of the model can be found in (Shaaban et al. 2021). ViSA model has been developed as part of the project "Digital Agricultural Knowledge and Information System (DAKIS)" (https://adz-dakis.com/en/) which aims at developing a decision support system that supports farmers in agricultural management choices with real-time digital data and spatial information. Hence, this will enable the resource efficient sustainable production of commodities, ESS and biodiversity and to precisely stimulate cooperation among farms (Mouratiadou et al. 2021). The model is designed to investigate three case study areas (CSAs) in Germany at a sub-district landscape scale (approx. 650 km^2) in Brandenburg region: 1) Märkisch-Oderland (MOL), 2) Ostprigniz-Ruppin (OPR) and 3) Uckermark (UMK). In this version of the model, we test the model in MOL only, however, the Corine Land Cover (CLC) data for the other two CSAs are included in the model. In the following sections we follow the description items of the ODD protocol.

2. Purposes

There is a lack of ABMs that address the bottom-up demand-driven management of ESS provision at a landscape scale in agricultural system under the social-ecological framework and consider simultaneously the non-monetary values of such ESS in terms of different types of capitals. Most of the existing ABMs are concerned with assessing the effect of different top-down policies on land use/land cover change, the economic viability of farmers and the promotion of ESS. To that we attempt via ViSA model to address research questions relating to the feasibility of ABM to spatially identify hotspots of supply-demand gaps; how to minimize these gaps and the anticipation of system evolution under different scenarios. The aim of ViSA is to simulate the adaptive dynamic interactions between different stakeholders representing the agents within the social-ecological agroecosystem and identifies conditions and scenarios that support the viability of the system through assessing the impacts of different management options and decision behaviors on the evolution of the supply-demand gaps and conflicts between stakeholders. The model has been programmed in the open-source software Netlogo 6.1.1 (Wilensky 1999).

3. Entities, state variables, and scales

We have in ViSA three main entities: 1) the actors who represent spatial agents. In this version, we include only three actors representing an organic farmer (A), a nature conservation activist (B) and a conventional farmer (C). They are differentiated by their capitals which is further subdivided to capital types and their underlying representing parameters, the preferences to these parameters, their decision rules and the level, the location, the size of area and the type of demand for which ESS (i.e., biomass yield, erosion control, carbon sequestration, water availability and biodiversity), the management option applied to that area and their prioritization of the ESS. They are also characterized by state variables in terms of efforts they apply from their capitals and the utilities they gain out of their efforts in the management options used to increase the supply of the ESS. However, we represent these actors by spatial cells that correspond to the location of the demands for ESS. We assume that the capitals of the actors in each demand area are the same since they are for the same person. In the hubnet feature, actors are represented by agents; 2) the ESS supply, which are represented by spatial units also but covering the whole CSA. They differ by the level and the location of the supply, the rate of restoration, the rate of depletion and their unit utility according to each management option; 3) the marginal values of the ESS, policy and regulations and external incidents in terms of disasters, wars or outbreaks that represent the environment that drive the behavior and dynamics of all agents. One time step represents one month and simulations were run for 30 years (from 2021 – 2050). There are three spatial resolutions embedded in the model: 100 m^2 (1 ha), 0.25 km^2 (500 x 500 m) and 1 km^2. The model landscape scale is approximately 650 square kilometers for each of the three CSAs. The variables that have been created in the code of the model and their definition can be found in the supplementary material (SM). Here below a list of variables used in the submodels:

Δs_x^k	The change of supply of ESS (k) at spatial location x
r_x^k	Restoration rate
P_x^k	Maximum potential supply of ESS (k) at spatial location x
s_x^k	Current supply of ESS (k) at spatial location x
N_x^k	Natural or anthropogenic incidents reducing the supply of of ESS (k) at spatial location x (e.g., climate change, natural disasters or wars) representing the external system
H_x^k	The amount of ESS k that can be added or reduced from the existing supply at spatial unit x due to human intervention
q^k	The efficiency of the management option applied by an actor in changing ESS k (i.e., the amount of supply increased or decreased for a unit of effort)
E	The total efforts applied towards applying a management option to change the supply of all ESSs in all areas of demand in the landscape
E_x	The total efforts applied towards applying a management option to change the supply of all ESSs at spatial location x
E_x^k	The total share of effort the actor spends from his/her capital allocated to change the supply of ESS (k) at spatial location x
E^+	The maximum effort to be applied by an actor
p_x^k	The priority to ESS (k) at spatial location x
d_x^k	The demand level for ESS (k) at spatial location x

s_{per}	The perceived supply level of ESS (k) at spatial location x
e_x^k	The unit effort which is the effort required to make a unit change of ESS k at spatial unit x
K_a	The total capital of actor a including all types of capitals
$i_{m,cap}$	The value of individual indicator m of capital type cap that the actor possesses in terms of capitals K_m; spends in terms of efforts E_m; gains in terms of utilities U_m
w_m	The weight (preference) of indicator m
i_{cap}	The value of capital type cap that the actor possesses in terms of capitals K_{cap}; spends in terms of efforts E_{cap}; gains in terms of utilities U_{cap}
$U_{x,a}$	The total utility gained by actor a at spatial location x due to the captured values from the changed supply of all ESS $\sum_k u_x^k H_{x,a}^k$ after the application of efforts $E_{x,a}$
u_x^k	The unit utility gained (price) due to a unit change in the supply of ESS k
u_0	The initial unit utility
z	The slope of the curve that reflects the elasticity of the unit utility to a change in ESS supply due to human intervention
σ_a	The impact on the utility from self-efforts of actor a
ω_{ab}	The mutual coupling between efforts and utilities of other actors (i.e, The impact of the effort of other actors b on the utility of the main actor a with whom they interact at the same spatial unit)
β	The adaptation rate at which the actor changes the amount of applied efforts in a specific management option required for changing the supply of an ESS in proportion to the incremental change of the overall utility they experience as a result of the interaction with other actors (i.e., The inverse of the response speed of changing the efforts)
α	The adaptation rate at which the actor changes the amount of the priority of an ESS by comparing the marginal value of that ESS v_a^k with the weighted average marginal values of all ESSs $\sum_l p_a^l v_a^l$ (i.e., The inverse of the response speed of changing the priority)
v_a^k	The marginal value of an ESS that reflects the incremental change of utility with the change in priority $\frac{\partial U_a}{\partial p_a^k}$
$\sum_l p_a^l v_a^l$	The weighted average marginal values of all ESSs
U_a^*	The target utility at which the utility will neither change by changing the efforts (i.e. $\frac{\partial U_a}{\partial E_a} = 0$) nor by changing priority (i.e. $\frac{\partial U_a}{\partial p_a^k} = 0$)
E^*	The target effort at which the utility will not change to which the actor optimize the efforts
p_a^{k*}	The target priority of ESS k by actor a at which the utility will not change to which the actor optimize the priority of ESS
F^k	The total effective effort that is applied by the actors collectively to increase the supply of ESS k
F_a^k	The effective effort by actor a to increase the supply of ESS k in cooperation with other actors
F^{k^*}	The target total effective effort at which the supply of ESS k reaches a state of equilibrium (i.e. $\Delta s_x^k = 0$)
γ^k	The adaptation rate at which all actors collectively change their total effective effort to reach the target one (i.e., the inverse of the response speed of changing their effective effort)
φ_a^k	The share of effective effort by actor a to increase the supply of ESS k
ΔE_a^k	The change of individual effort applied by actor a to increase the supply of ESS k

4. Process overview and scheduling

ViSA model contains 10 major procedures as shown in Figure 1 though not all of them are necessary to run the model but they add some more features to the model as will be explained in details in the following points. Procedures 1 – 4 are the most important ones to run a simulation and get outputs whereas the rest are auxiliary.

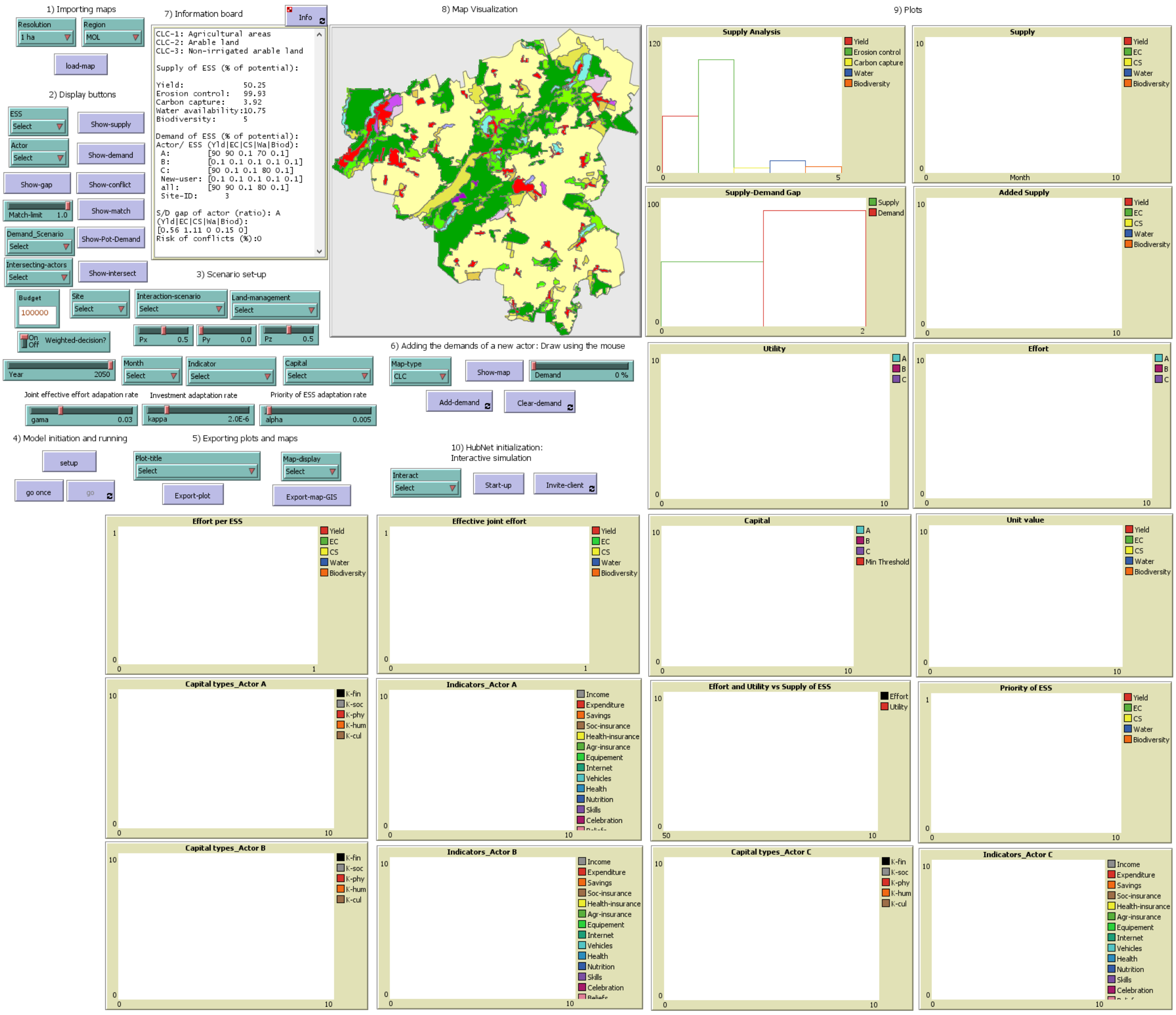


Figure 1. The interface of ViSA model

4.1. Importing maps

In this step all geodata with WGS 1984 UTM Zone 33N GIS projection relevant to the CSA under investigation are imported to the model after selecting the CSA (Fig. 2c), the resolution level (Fig. 2b) at which the data are displayed then pressing “load-map” button (Fig. 2a). Here, we have three levels of resolutions from low to high: 1 km, 500 m and 100 m (1 ha). However, at high resolution, the model is very slow. Thus, we set 500 m as the default one. Since the supply as well as the demand maps of the ESS do not necessarily cover the whole CSA, the empty cells within the political boundaries in Netlogo display the string “not a number” (NaN) to that variable. This string hinders mathematical operations that use that variable giving an error message. In order to avoid such errors, we replaced these NaN inputs with 0 and 0.1 values for supply and demand geodata, respectively.

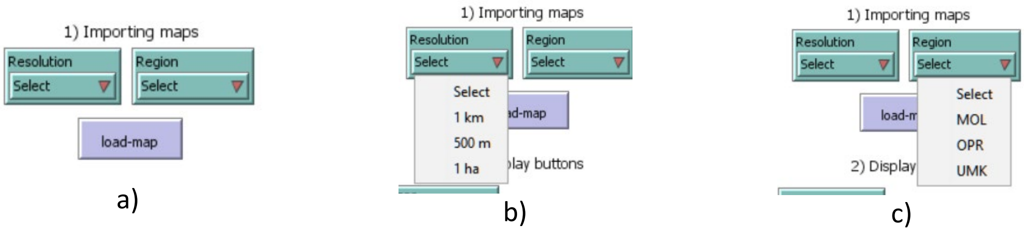


Figure 2. Buttons used to load geodata to the model

The geodata imported include:

a) Supply maps in raster format for the five ESS. The maps include normalized values of their corresponding real values. The normalization has been conducted using ArcGIS 10.6.1 software. The supply maps are based on data from the Federal Institute for Geosciences and Natural Resources for biomass yield (BGR 2013) and for water availability (BGR 2015), the Joint Research Centre-European Soil Data Centre for soil erosion (ESDAC 2015, Panagos et al. 2015) and carbon sequestration (ESDAC 2004, Jones et al. 2005) and the European Environment Agency (EEA et al. 2012) for biodiversity.

b) Demand for ESS maps of the three actors in vector format (shape files). The level of the demand and the ID of each demand area for each ESS by each actor is imported to a specific patch variable. The demand maps have been generated for MOL only in this version using the online participatory GIS tool "Maptionnaire" that has been used to collect the empirical data (Schwartz et al. 2021).

c) The political boundaries of the case study areas which have been obtained from the Corine Land Cover (CLC) geodata (Copernicus Land Monitoring Service - European Environment Agency 2018) for the CSAs and is used additionally to identify three levels of land use and visualize as well the land use in the CSAs based on the standard RBG (red, blue, green) values used for each land use.

4.2. Display buttons

This procedure presents seven functions (represented by the seven blue buttons in Fig. 3a) related to visualizing data on the view and identifying the ESS and the actor to be investigated:

i. By selecting one of the ESSs from the drop-down button "ESS" (Fig. 3b), then pressing "show-supply" button, the supply map of that ESS will be displayed with scaled-color corresponding to the values of the supply in each patch (Fig. 4a for yield and 4b for carbon sequestration) (red = yield, green = erosion control, yellow = carbon sequestration, blue = water availability, orange = biodiversity). The source of data will be in parallel displayed on the information board.

ii. By selecting one of the actors from the drop-down button "Actor" (Fig. 3c), then pressing "show-demand" button, the demand areas for the selected ESS by that actor will be displayed on the view with scaled-color (Fig 4c). Simultaneously, the values of the demand in each area are displayed on the information board corresponding to each demand site. It is possible also to display the demands for all ESSs by one actor by selecting "mix" from "ESS" button, the demands for one ESS by all actors by selecting "all" from "Actor" button or the demands for all ESSs by all actors by selecting "mix" and "all" from both drop-down buttons followed by pressing on show-demand button (Fig. 4d).

iii. By pressing on the "show-gap" button, the supply-demand gap in terms of a ratio of supply to demand (S/D) will be displayed on the view with scaled-cyan color (Fig. 4e). The darker the color is, the lower the gap will be (i.e., perfect supply-demand match when gap = 1). Fig. 4f shows the gap after running the model. In order to visualize the gap, we set a range between > 0.01 and < 10. This is because we assume that in case the supply is 100 or 10, any demands below 10 or 1, respectively, will be neglected or if the demand is 100, any supply below 1 will be neglected. Thus, we try to avoid very low demand or supply values.

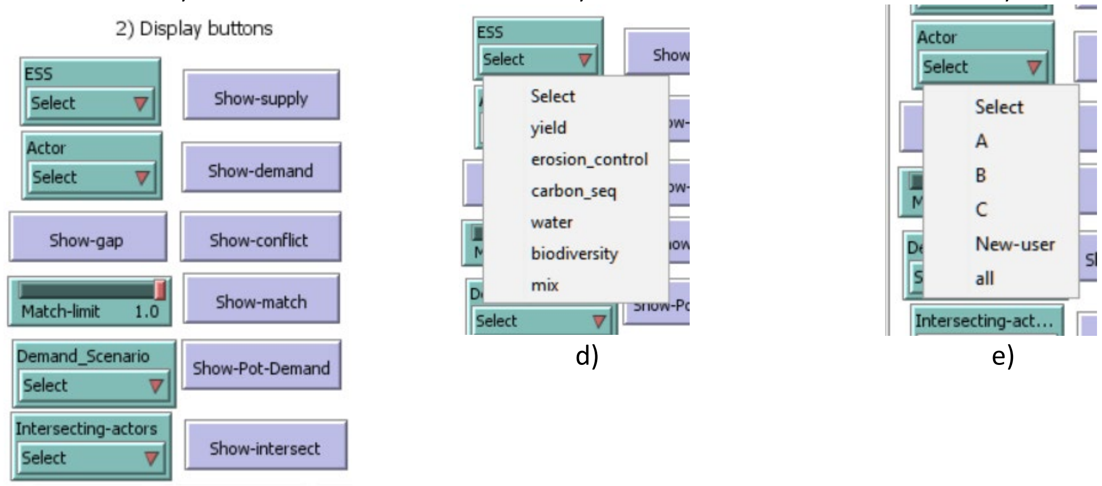
iv. By pressing on the “show-conflict” button, locations and level of risk of conflicts will be displayed on the view with scaled-violet color (Fig. 4g and Fig. 4h after running the model). Risk of conflicts are displayed only on patches with demands for yield and biodiversity by two different actors since they exhibit tradeoff characteristics. It is calculated as the absolute difference between the supplies of these two ESS.

v. By pressing on the “show-match” button, patches with perfect matching of supply with demand will be displayed. The slider “match-limit” button can be adjusted such that the actor can set a fraction of the demand level to the minimum threshold to find alternative sites in the landscape where the demand can be satisfied (e.g., 0.6 of 90 in Fig. 4i). This function corresponds to a decision-adaptation scenario called “supply-driven demand adaptation” (Shaaban et al. 2021) in which the actor attempts to satisfy his/her demands for ESS by adapting the demand to the existing supply either by changing the demand site, reducing the demand level or even both.

vi. The “show-Pot-Demand” function represents another approach to satisfy demands in space without applying a management option. The idea here is to identify the demand level from the “Demand_Scenario” drop-down button, which contains the values of the demand levels of the three potential demand sites set by the actor or the average of their values (Fig. 3d). The demand value will be set to all patches within the CSA except the demand sites with different demand values (Fig. 4j). By pressing on “show-gap”, the actor can search for the sites with minimum supply-demand gap which corresponds to dark cyan color (Fig. 4k).

vii. The show-intersect button is to inform only on the patches where the demands for any ESS of the actors intersect. This can be checked between each two actors or between all actors by selecting from the drop-down button “intersecting-actors” whom we would like to check (Fig. 3e). Then, by pressing on the show-intersect button, patches with intersecting demands will be displayed in black (e.g., between actor B and C in Fig. 4l). This function helps identify sites where conflicts or cooperation might exist.

a) b) c)



d) e)

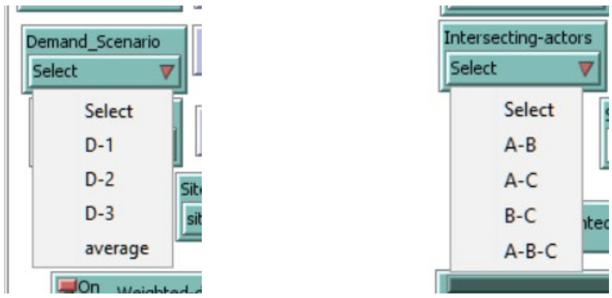


Figure 3. Display buttons of the model

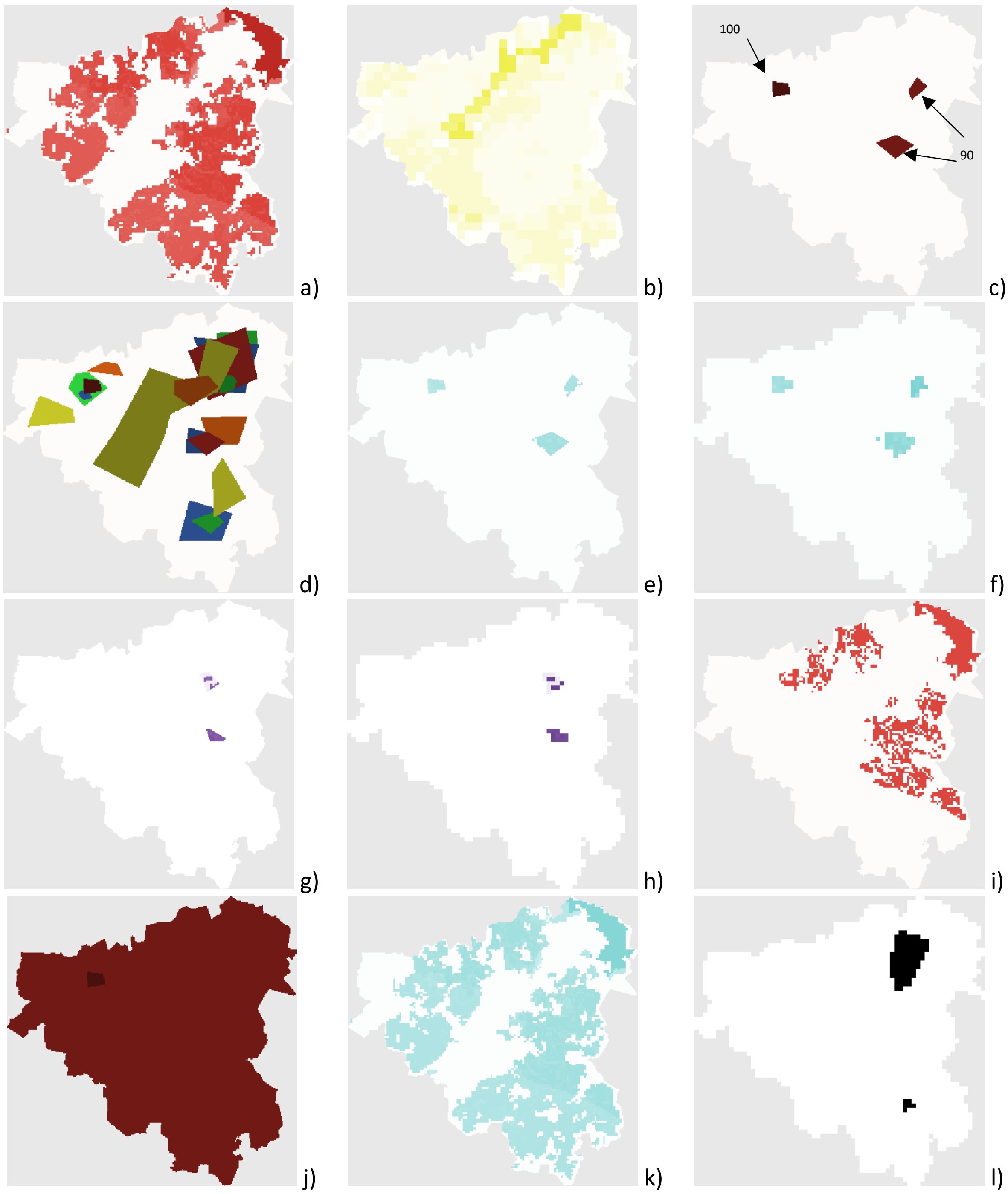
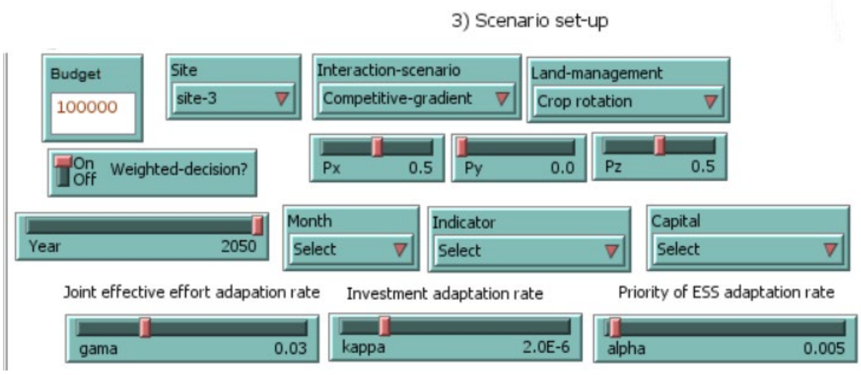


Figure 4. Visualizations that can be displayed on the view using the display buttons

4.3. Scenario set-up

This procedure (Fig. 5a) is important in setting up the initial condition, the area to be investigated and the scenario to be tested. The budget button is used to identify the amount of money that is given to the actors as a payment to be invested in promoting the supply of ESS. Three drop-down buttons are used to identify the scenario to be investigated. First, the site button (Fig. 5b) identifies which demand site will be investigated. This should be preceded by selecting the actor and the ESS from their corresponding drop-down buttons. During demand data collection, the actors were asked to specify maximum three demand areas only for each ESS. Though, the model runs over the whole landscape, we present the results on the plots only for one demand site but on the view the three demand site are visualized. Second, the interaction-scenario drop-down button (Fig. 5c) identifies which decision behavior is taken by the actors. We investigate here three decision rules: 1) competitive-gradient, in which the actors compete on the supply of ESS with an objective of continuously maximizing their utilities by adapting their preferences to the ESS with the highest return on their capitals; 2) competitive-optimizing, in which the actors still compete on the land but they set a target objective for their investments and priority towards ESS at which the utilities will not change by further changing their investments or priorities; 3) cooperative-optimizing, in which the actors cooperate through setting a joint effective effort to which each actor contributes to increase the supply of ESS. Third, the land-management button (Fig. 5d) which specifies which management options will be applied on the demand sites to improve the supply of ESS. We suggested here three management options: i) crop rotation, which includes implicitly patch cropping and smart farming, ii) hedges and iii) agroforestry. It ought to be noted that the impact of these options on the supply of ESS is based on default data for the design of this version of the model. However, the model will be coupled with another model that measures these impacts. The three sliders Px, Py and Pz are linked to the management options, respectively. They are used to test a mix of two or three management options with a share identified through these sliders. The weighted-decisions switch is used to run the model either by considering the preferences of the actors to the parameters of the capitals or by keeping it neutral. Two buttons are used for identifying the time period till which the simulation runs. The year sliders identifies the year which spans from 2021 till 2050. The month drop-down button (Fig. 5e) identifies until which month the model runs. The last two drop-down buttons indicator (Fig. 5f) and capital (Fig. 5g) can be used to display the results either for one parameter or one capital type, respectively, instead of displaying the results for the total capital. Thus, each parameter or each capital type can be assessed individually. We have here also three sliders that are used to identify the adaptation rates (i.e., inverse of the response speed of the actors to the changes in their utilities) which ranges between 0 and 1. The gamma button is used for the cooperative scenario only, whereas the kappa, which is the adaptation rate of efforts, and alpha, which is the adaptation rate of priorities, are used for the competitive scenarios (see Table 1).



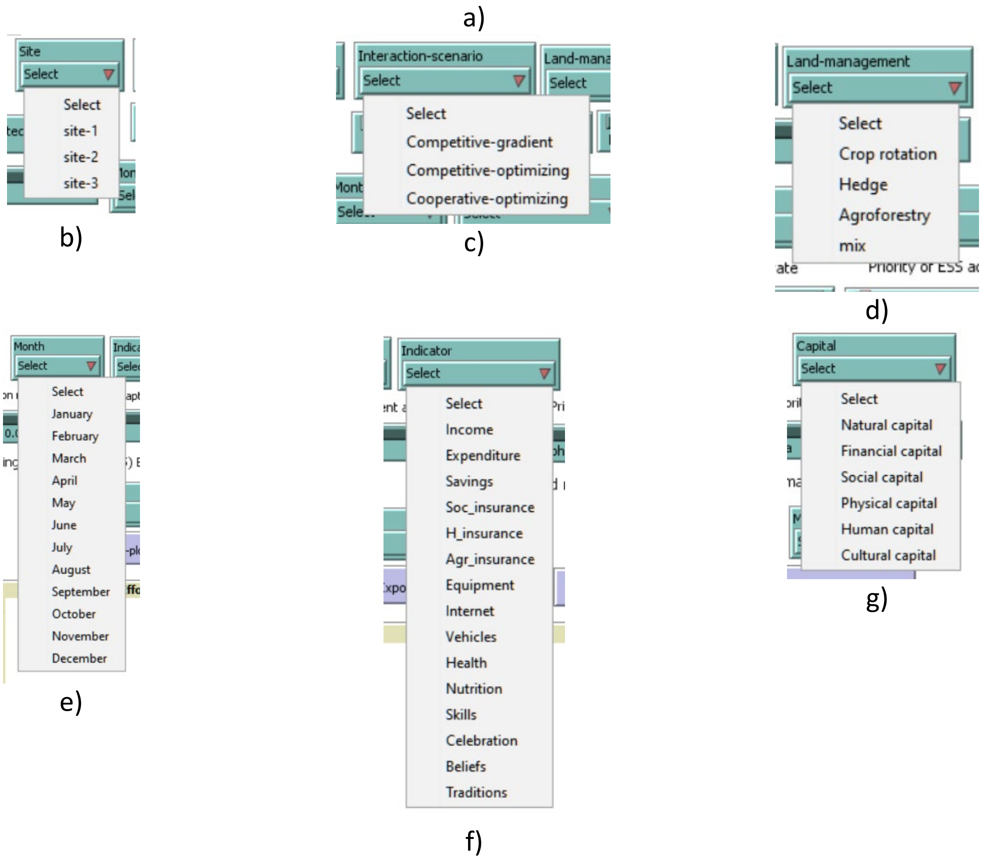


Figure 5. Scenario set-up button

Table 1. The values of the adaptation rates used in the model

Scenario	alpha	kappa	gama
Competitive-gradient	0.005	0.000002	N.A.
Competitive optimizing	0.05	0.0000002	N.A.
Cooperative-optimizing	N.A.	N.A.	0.03

4.4. Model initiation and running

This procedure is used to assign the initial values to the variables other than those imported from the geodata by pressing the setup button. These values are included in the code of the model either as individual values or as a matrix of data. These covers the capitals of the three actors at the parameter level, the preferences to these parameters, the efforts needed for the three management options, the unit utilities gained from the management options, the elasticity of these unit utilities and their efficiency in increasing the supply of ESS. Further, the values are normalized during this procedure. The other two go buttons is used to run the model. The go-once button runs the model for one time step whereas the go button runs the model continuously until the defined duration. In this version of the model, we tested it with values changing yearly for 10 years. The duration mode can be activated from the code of the model by deleting the semicolon before “if ticks >= duration [stop]“ line under go procedure and deactivating the below line which uses 10 instead of duration by adding a semicolon before it. However, since we use in the model unreal data, errors could develop due to very low values of the variables could result while running it at a monthly resolution. Under go procedure, the values of some variables such as the supply of ESS, the parameters of the capitals types, the values, the efforts, the priorities of the ESS by the actors and the unit utilities change. Three sub-procedures (i.e., reporters) are included in the setup and go procedures which are used for the calculations of interim variables used later in the calculations of main procedures such as the self-benefit and the mutual-benefit in the calculate intermediate and calculate derivative reporters, respectively.

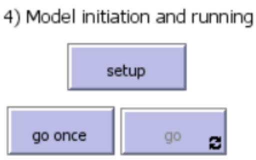


Figure 6. Model setup and running buttons

4.5. Exporting plots and maps

This procedure in Fig. 7a is concerned with exporting the generated plots to a comma-separated values file (CSV) and the visualizations to a raster geodata which can be reused in another application or in the final decision support system of the DAKIS project. The plot-title drop-down button (Fig. 7b) is used to select which plot to be exported out of the 16 plots in the list. The plots that can be exported are described in section 4.9 (Fig. 4c – 4r). The map-display drop-down button (Fig. 7c) is used to select one of the four visualizations that is displayed on the view to be exported. The main visualization that can be exported are the demand, though this will not change but to be sure that it matches with input data, the supply, the gap and risk of conflicts which change with running the model.

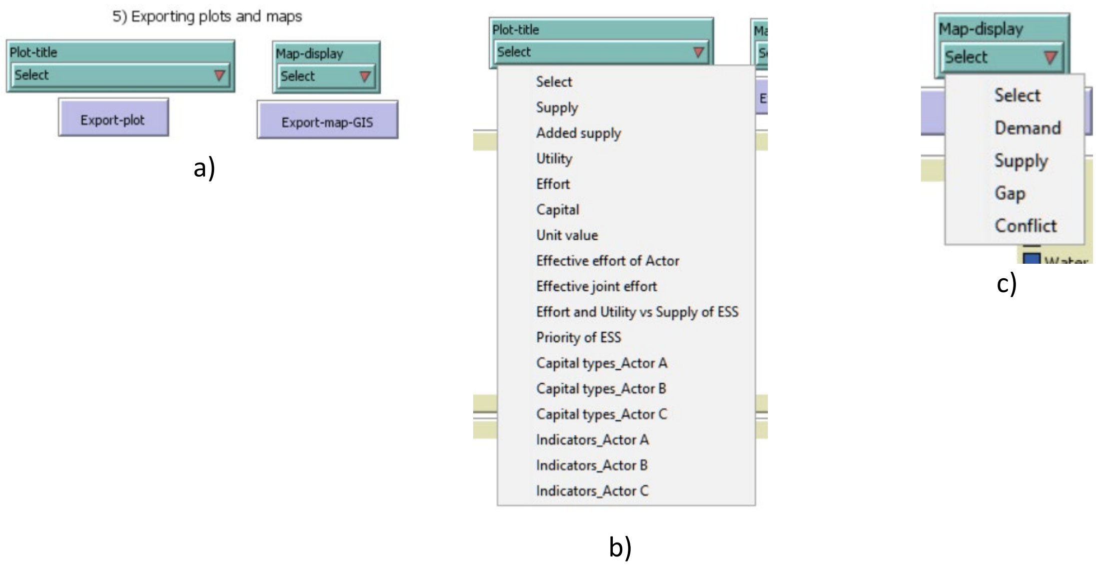


Figure 7. Buttons for exporting maps and plots

4.6. Adding the demands of a new actor

The aim of this procedure (Fig. 8a) is to include a new actor in the assessment with a direct addition of the demand via the model. First, the user select one of the base map to be displayed in the view from the map-type drop-down button (Fig. 8b). Three possibilities can be chosen: 1) the CLC, which displays the Corine Land Cover but without legend (Fig. 8c), however, the land use type can be detected via the procedure in Section 4.7, 2) the satellite map (Fig. 8d) or 3) the basic map (Fig. 8e). The last two are images imported to the view. Then, the user select from actor drop-down button “New-user” and select from the ESS drop-down button the ESS for which he/she has demand. The demand level can be set via the slider “Demand” in Fig. 8a, then, press on add-demand button and start drawing by clicking on the mouse while the arrow stands on the view to add the demand areas. This can be repeated for the five ESS. Erasing an added demand area by mistake can be accomplished by pressing on clear-demand button, then erasing those drawn areas. Fig. 8f shows an example of added demands via this procedure to a new-user.

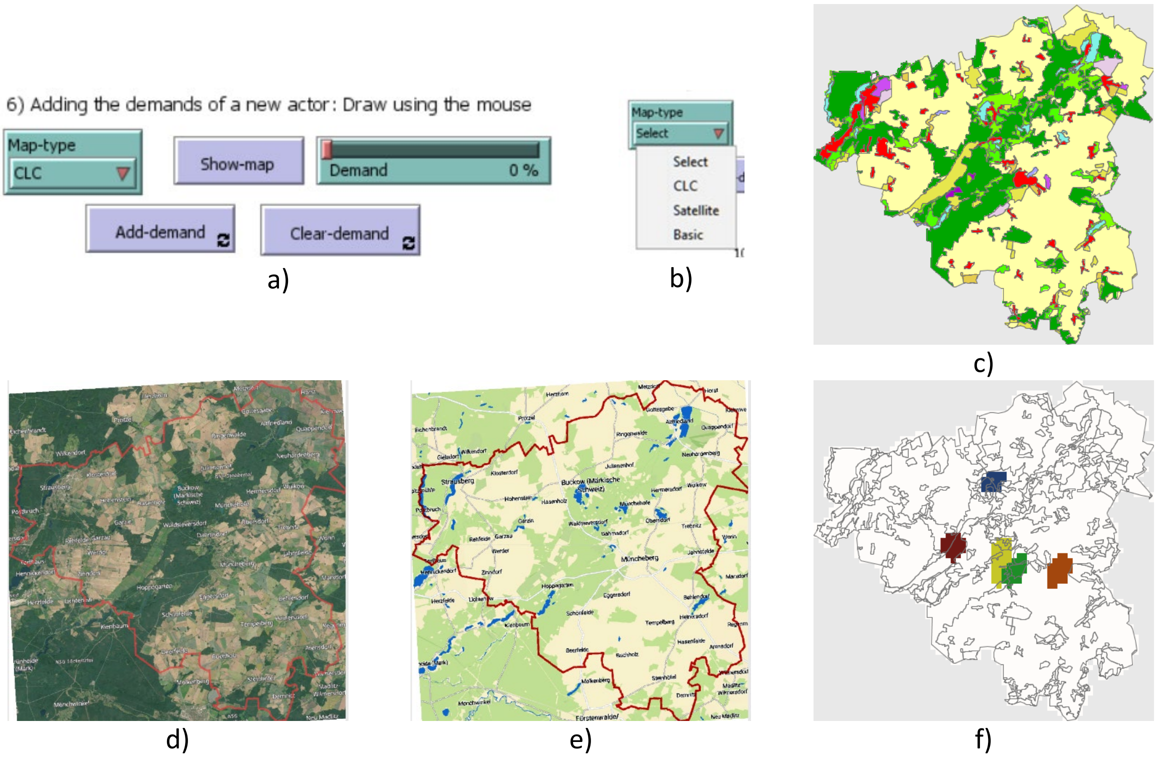
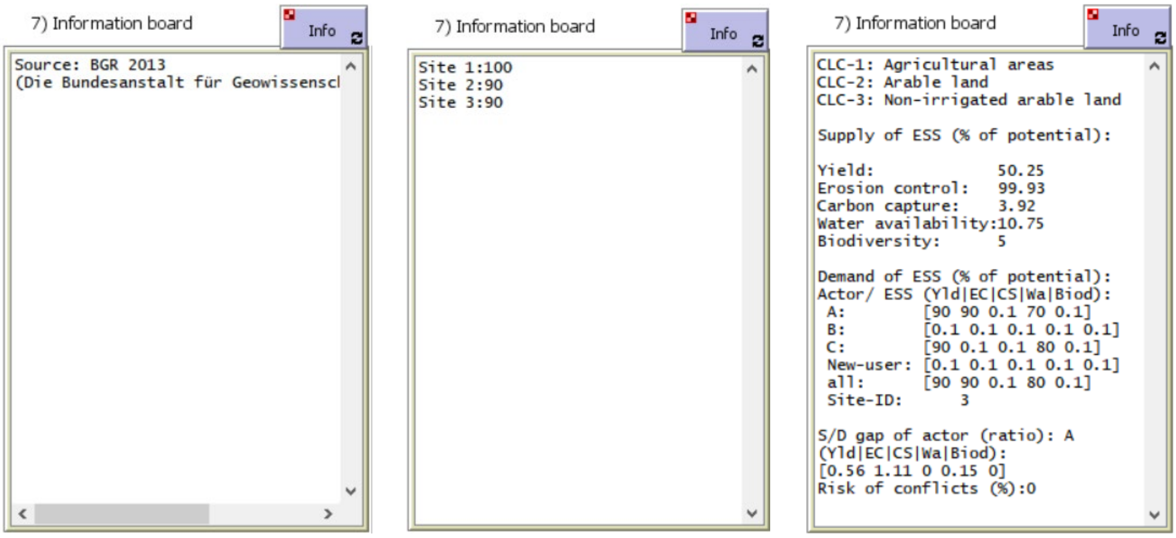


Figure 8. Testing the demand of new actor buttons

4.7. Information board

This procedure functions as an alternative to the legends that translate the visualizations presented on the view, however, not so accurate as normal map legends. It presents information in three cases: 1) after pressing the show-supply button, it displays the source of the supply geodata (Fig. 9a), 2) after pressing on the show-demand button, it displays the demand level in each of the potential three demand sites for the selected ESS (Fig. 9b), 3) after pressing on info button in Fig. 9 followed by clicking on the mouse on any patch on the view within the landscape, a detailed information about that patch will be displayed as shown in Fig. 9c. It shows the land cover type at three levels, the supply level of the five ESS, the demand level for the five ESS by the three actors, the new-user if added and all actors, the ID of the site so that one can detect which demand site will be assessed in the simulation, the supply-demand gap of the five ESSs and the risk of conflict at that patch. The patch size reflects the resolution. Thus, at 1 ha resolution, the patch size is one ha. Moreover, the supply data of the five ESS and the supply-demand gap are simultaneously plotted on the two plots presented in Fig. 10a and 10b, respectively.



a) b) c)

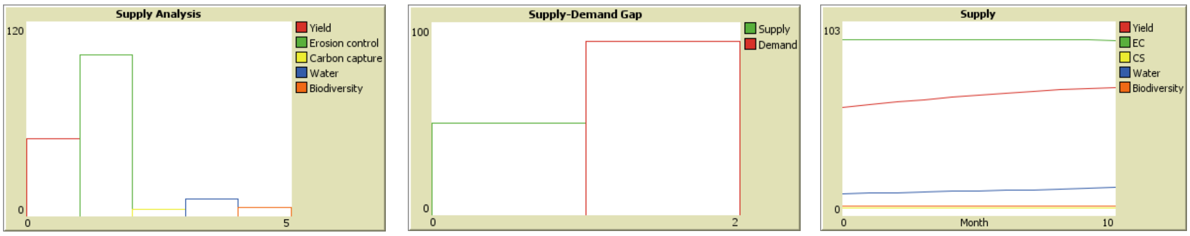
Figure 9. Information board displaying the land use type at three levels, the values of demands, supply, the ID of the site to be investigated, gap, risk of conflict on the selected patch. It also displays the source of the supply maps when show-supply is dressed and shows the level of the demand in each area when show-demand button is pressed (Yld = yield, EC = erosion control, CS = carbon sequestration, Wa = water availability, Biod = biodiversity)

4.8. Map visualization

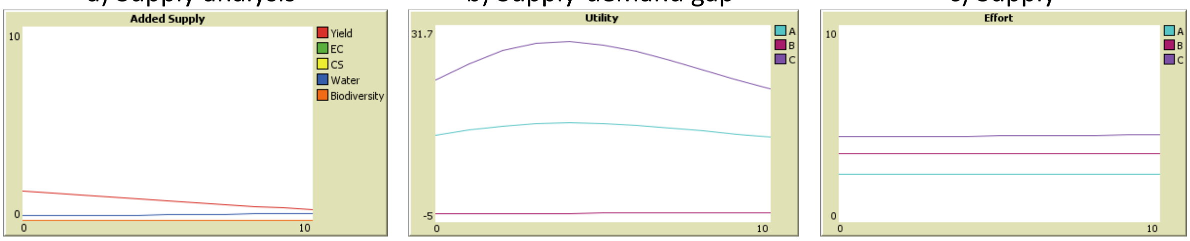
This is basically the spatial representation of the data on the view of the model that has been shown in the previous sections and can be exported as a raster geodata for further investigations or processing.

4.9. Plots

This procedure shows 2 plots (Fig. 10a and b) that display data about the supply and demand level when clicking on the view (see Section 4.7) and 16 plots (Fig. 10c – r) that display the change in specific variables with time during running the model (N.B. Fig. 10j shows the change in effort and utility with supply).



a) Supply analysis b) Supply-demand gap c) Supply



d) Added supply e) Utility f) Effort

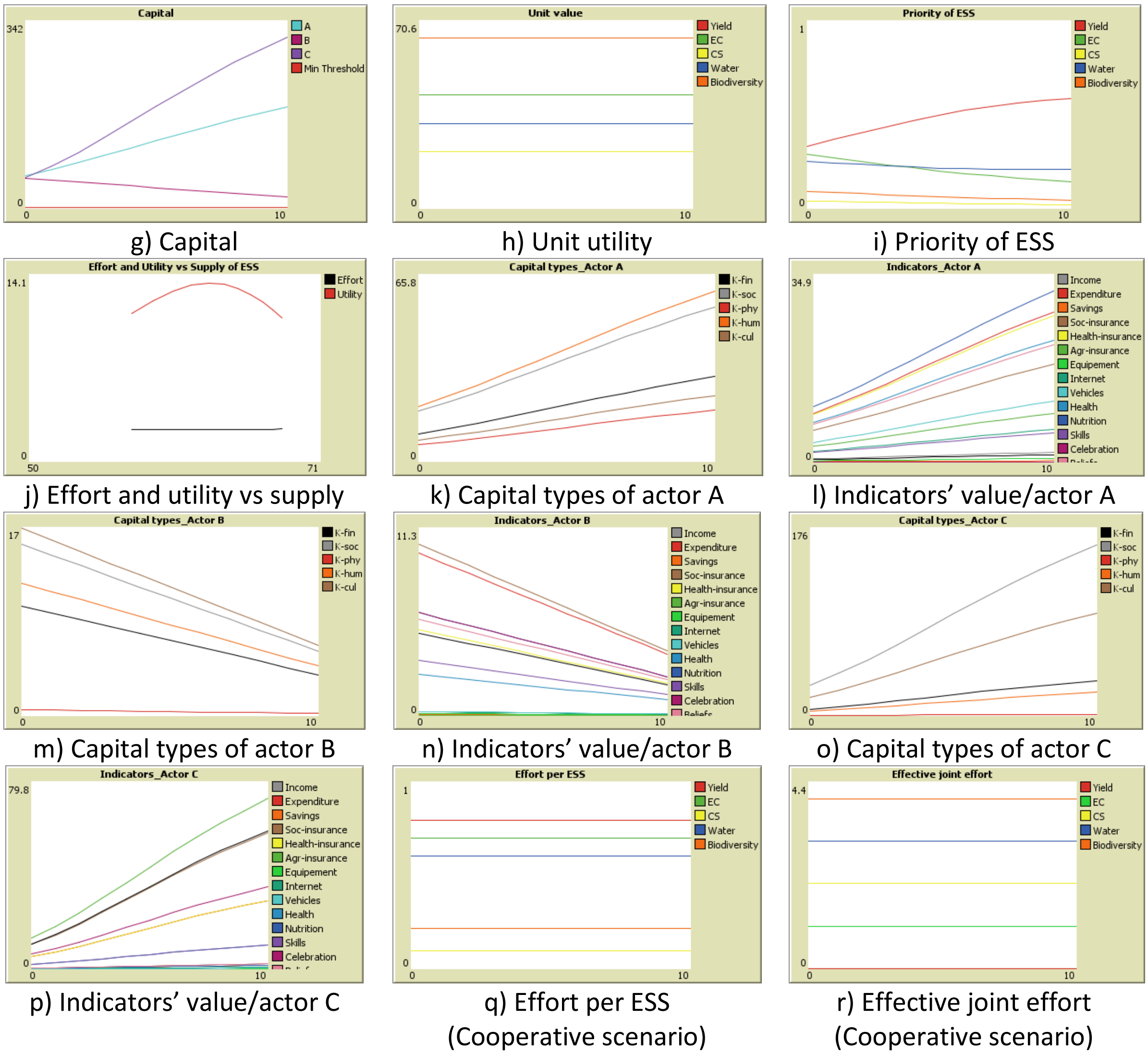


Figure 10. Simulation results displayed on plots

4.10. HubNet initialization

This procedure represents an added function of combining role-play games with ABM but still under development. It utilizes the hubnet activity of Netlogo in connecting several actors to the model so that they can interact directly. The start-up button in Fig. 11a initializes the hubnet connection through opening a pop-up window asking to start a new session with a suggested name and broadcasting the server location. Then, a new small window opens showing the server address and port number that should be communicated with the players to connect to the model. They enter these data in Netlogo HubNet Client tool and their given name, then, the hubnet client window (Fig. 11c) will open in their computers proofing that they are connected. In order to interact with the model, the invite-client button should be pressed. In this version, we just enable simple tasks to the clients so that they can remotely interact with the model such as displaying the supply on their view, showing the demand areas for selected ESS of other actors and add new demand areas to themselves as new users. In this procedure an agent per each actor is created with a shape of a man. They can get the data about the supply and demand levels in each patch by moving this agent using the direction buttons in their client windows. This is used also for adding a new demand or erasing it (Fig. 11b). This procedure will be further developed so that each actor can select one or a mix of the management option to be applied in their demand sites and get feedback on the impact of this decision on the capitals and the supply of ESS so that they either maintain their decision or adapt it according to its impact. Two plots from the main server are mirrored on the client window.

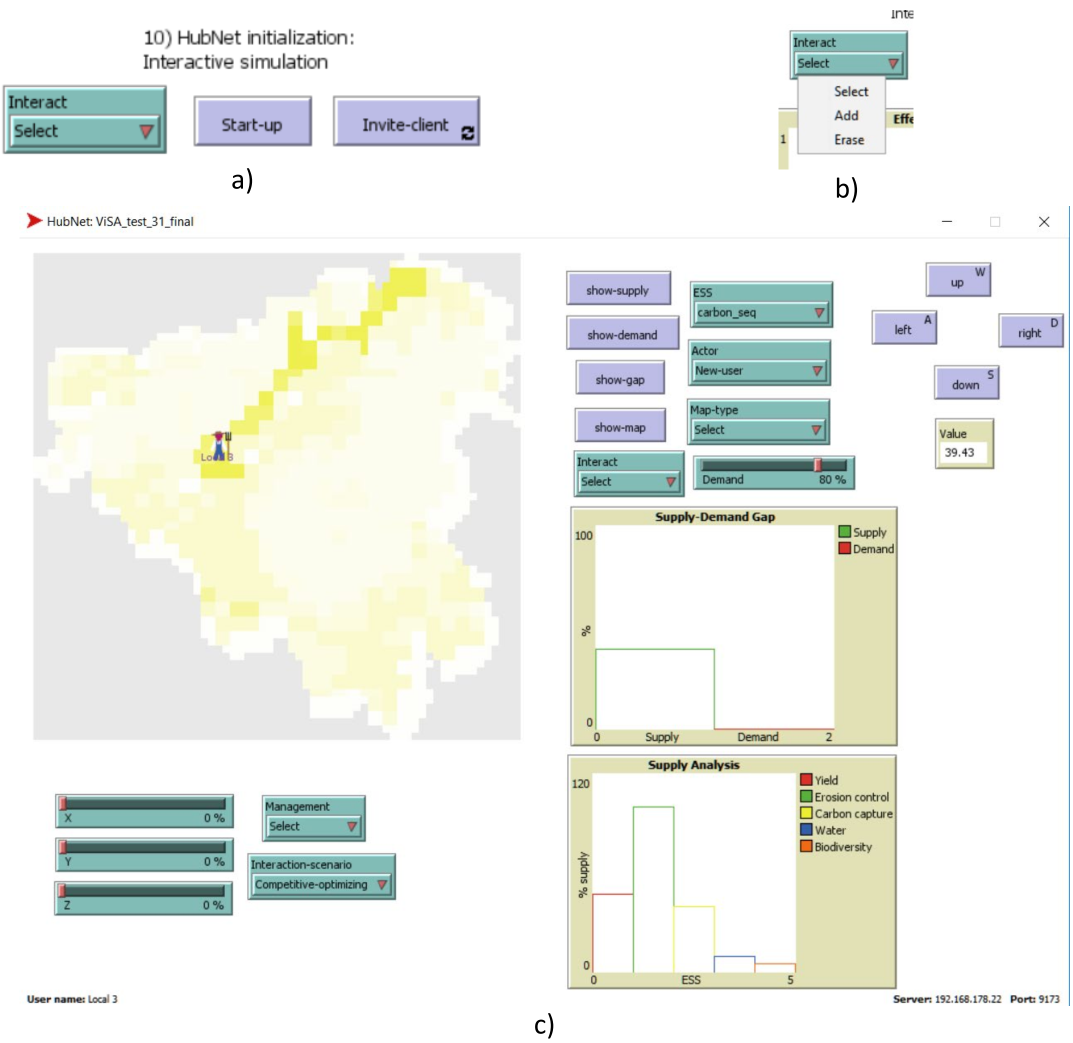


Figure 11. Buttons used to initate hubnet connection procedure and the client interface

5. Design concepts

5.1. Basic principles

ViSA model is an extension to the VIABLE (***V****alues and* ***I****nvestments from* ***A****gent-****B****ased interaction and* ***L****earning in* ***E****nvironmental systems*) model that has been developed by BenDor & Scheffran (2018). The VIABLE model is used for complex system analysis and integrates a bundle of approaches, namely, ABM, system dynamics, evolutionary game theory and network analysis. It describes the framework of maintaining a dynamic system within constraints defined by value-based judgments or objective limits according to the viability theory introduced by the mathematician Jean-Pierre Aubin to (Aubin 1991, BenDor & Scheffran 2018). ViSA, as compared to VIABLE, considers non-monetary as well as monetary value system in the judgements of the agents and involves the geographical spatial dimension in its analysis.

The basic principles of the ViSA model is to depict system evolution as a result of the interaction between several actors' groups with each other and with the ecological system that provides them with benefits from ecosystem services in agricultural landscapes. Actors allocate part of their efforts that originates from different types of capitals (i.e., financial, social, natural, physical, cultural and human) to increase the supply of the ESS of interest. These ESS have a unit utility (i.e., price) which also spreads over these different types of capitals. The added supply of these ESS builds up the utility that is ultimately increases their capitals. In this version, three management options (1. Crop rotation with Smart farming/patch cropping, 2. Hedgerows planting, and 3. Agroforestry system application) are suggested to be implemented by the actors to increase the supply of ESS. In some locations in the landscape, several actors shows demands for ESS that have tradeoff nature. This issue triggers conflicts between actors. Thus, they either decide to compete or to cooperate with actors sharing demands in the same location. Further, they can either adapt their preferences to the ESS by shifting their priorities to those with the highest marginal values (gradient decision rule) or they set a target priority at which their utilities will no longer change (i.e., optimizing decision rule). Actors attempt to compromise between the viability of their capitals and the viability of the ecological system via satisfying their demands for ESS.

5.2. Emergence

The key outputs of the model are the change in: 1) the different types of capitals of the actors with the underlying indicators that reflects the monitoring of social viability, 2) the supply of the ESS due to the application of the management options with an objective of reducing the supply-demand gap, 3) the risk of conflicts in the joint demand areas 4) the priorities of ESS by each actor and 5) the unit utility of the ESS in terms of each parameter of the different types of capitals.

5.3. Adaptation

Actors adapt mainly their efforts and priorities towards the ESS according to the utilities they gain from these ESS. Adaptation rates can also differ from one actor to another though in this version we apply the same adaptation rates to all actors. Their decision rules emerge from their initial preferences to the parameters representing their capitals and they wish to increase. Further, they can opt either to cooperate or compete with other actors. Actors also apply one of two decision objectives. On the one hand, they can follow the gradient rule in which they compare the marginal value of one ESS with the weighted average marginal value of all ESS and shift to the maximum marginal value. On the other hand, they can follow the optimizing rule, in which they try to attain target efforts and target priorities at which their utilities will no longer change.

5.4. Objectives

The main objectives of the actors is to reduce the supply-demand gaps of ESS while maintaining the viability of their capitals. However, we simultaneously aim at reducing the risk of conflicts that could arise between actors having demands for ESS showing tradeoffs in their supply by testing several mixes of management options.

5.5. Learning

In this version of the model, we do not include learning process but rather we simulate the system according to the initial input data. However, we added a hubnet feature to the model to allow in the future for live role-playing games in which actors learn from their decisions at when time step and can change it at future time step. Further, this will be connected to a machine learning approach to assist in learning the decision behaviors of actors and in creating virtual actors imitating the real world.

5.6. Prediction

We assume here conceptual prediction sub-models related to the impact of management options on the supply of ESS (i.e., efficiencies) as well as the impact of policies, regulations and external factors on the whole social-ecological system (e.g., climate change models, pandemics, wars).

5.7. Sensing

Actors are assumed to sense their own data about initial state of capitals and priorities of ESS. Further, they sense the demands for ESS by other actors in their demand sites, the impact of other actors' efforts on their own utilities and on the supply of ESS. However, they do not sense the capitals of other actors, the initial existing supply of ESS, the efforts and utilities of management options.

5.8. Interaction

Two interaction scenarios are tested in the model: 1) the competitive one, in which the efforts of one actor reduce the utilities of another one, and 2) the cooperative scenario, in which actors share efforts in increasing the supply of ESS. This is represented by the mutual coupling of benefits submodel (Section 8, Equ. 10).

5.9. Stochasticity

Stochasticity is not included.

5.10. Collectives

Not included. The model runs on an individual base. However, for some stakeholders, it considers an organization or an association not the actor representing them as an agent. In this version of the model, we implement three individual agents (e.g. a farmer with his/her own charcteristics).

5.11. Observation

The main data collected from the model are: 1) geodata about the supply-demand gap, risk of conflicts and updated supply, and 2) data about the capitals of the actors at three levels: total capital, capital types and parameters of each capital as well as about the evolution of their priorities of ESS. Data can be collected at the time specified by the user during scenario setup step and they are free to use.

6. Initialization

Initial state at time zero in the model represents a proxy for the state of the system at 2021 due to some limitations in data availability and privacy. For instance, the supply maps of ESS dates back to 2004 – 2015. Further, we implement a hypothetical example with dummy actors. The assumed initial values of the parameters describing the actors, the management options, the supply maps and the CLC can be found in the supplementary material.

7. Input data

In this version, we use input data from the literature only about the supply geodata of ESS and the CLC. However, empirical data regarding the demands for ESS and the management options will be included in the next version of the model.

8. Submodels

The change in supply of ESS

$$\Delta s_x^k = r_x^k s_x^k \left(1 - \frac{s_x^k}{P_x^k}\right) - N_x^k + H_x^k \tag{1}$$

$$s_x^k(t+1) = s_x^k(t) + \Delta s_x^k \tag{2}$$

The capital type

$$K_{cap} = \sum_m w_m \, . \, i_{m,cap} \, , for \; cap = nat, fin, soc, phy, hum \; or \; cul \tag{3}$$

Normalization of the parameters

$$i_{m,norm} = \frac{i_m - i_{min}}{i_{max} - i_{min}} \cdot 100, (N.B. \, i_{min} = 0) \tag{4}$$

The added amount of supply during human intervention

$$H_x^k = q^k . s_x^k . \left(1 - \frac{s_x^k}{d_x^k}\right) . \frac{s_{act}}{s_{per}} . E_x^k \tag{5}$$

The unit effort

$$e_x^k = \frac{E_x^k}{H_x^k} = 1 \Big/ \left(q^k . s_x^k . \left(1 - \frac{s_x^k}{d_x^k}\right) . \frac{s_{act}}{s_{per}}\right) \tag{6}$$

The utility

$$U_{x,a} = \sum_k u_x^k H_{x,a}^k - E_{x,a} \tag{7}$$

$$U_a = \left(\sigma_a - \sum_b \omega_{ab} E_b\right) E_a \tag{8}$$

The self-benefit

$$\sigma_a = \sum_k \frac{u_0^k}{e_a^k} p_a^k - 1 \tag{9}$$

The mutual coupling of benefits

$$\omega_{ab} = \sum_k z^k \frac{p_b^k p_a^k}{e_b^k e_a^k} \tag{10}$$

The growth of capital

$$K_a = K_a + U_a \tag{11}$$

The competitive-gradient scenario

The change of efforts

$$\Delta E_a = \beta \frac{\partial U_a}{\partial E_a} = \beta E_a (E^+ - E_a) \left(\sigma_a - \sum_b \omega_{ab} E_b - \omega_{aa} E_a\right) \tag{12}$$

The change of priorities

$$\Delta p_a^k = \alpha p_a^k \left(v_a^k - \sum_l p_a^l v_a^l\right) \tag{13}$$

The marginal value

$$v_a^k = \frac{\partial U_a}{\partial p_a^k} = E_a \left(\frac{u^k}{e_a^k} - \left(\sum_b E_b z^k \frac{p_b^k}{e_b^k e_a^k}\right) - \left(E_a z^k \frac{p_a^k}{e_a^{k\,2}}\right)\right) \tag{14}$$

The competitive-optimizing scenario

The change of efforts

$$\Delta E_a = \beta \frac{\partial U_a}{\partial E_a} = \beta (E^* - E_a) \tag{15}$$

The change of priorities

$$\Delta p_a^k = \alpha \left(p_a^{k*} - p_a^k\right) \tag{16}$$

The target effort

$$E^{*} = \frac{(\sigma_a - \sum_{b \neq a} \omega_{ab} E_b)}{2\omega_{aa}} \tag{17}$$

The target priority

$$p_a^{k*} = \frac{(e_a^k)^2 \left(\frac{u^k}{e_a^k} - \left(\sum_{b \neq a} E_b z^k \frac{p_b^k}{e_b^k e_a^k} \right) \right)}{2 E_a z^k} \tag{18}$$

The cooperative-optimizing scenario

State of equilibrium of supply of ESS

$$r_x^k s_x^k \left(1 - \frac{s_x^k}{P_x^k}\right) + \left(H_x^k\right)_{management} = N_x^k + \left(H_x^k\right)_{damage} \tag{19}$$

The total target effective effort

$$F^{k^*} = \left(\frac{N_x^k + \left(H_x^k\right)_{damage}}{s_x^k} \right) - r^k \left(1 - \frac{s_x^k}{P_x^k}\right) \tag{20}$$

The change of total effective effort

$$\Delta F^k = \gamma^k \left(F^{k^*} - F^k\right) \tag{21}$$

The change of individual effort

$$\Delta E_a^k = \frac{\Delta F^k \varphi_a^k}{q_a^k} \tag{22}$$

The risk of conflicts

$$\mathrm{Conf.}\,(\%) = \left| \mathrm{s_{yield}} - \mathrm{s_{biodiversity}} \right| \tag{23}$$

9. Future extensions

It is planned to further develop the model by including real demand, real perceived supply and updated supply data; to simulate the demand adaptation in space according to the supply-driven demand adaptation pathway (see Shaaban et al. 2021); to include the dynamic exchanges of capital types; to test decision behaviors of actors via role-playing games using the hubnet activity and to couple it with qualitative scenarios generation to evaluate the probability of qualitative scenarios in the evolved system from individual actions.

10. References

Aubin, J.-P. (1991). *Viability theory*. Birkhäuser, Boston, Massachusetts, USA.

BenDor, T. K., & Scheffran, J. (2018). *Agent-based modeling of environmental conflict and cooperation*. Taylor & Francis, Boca Raton, Florida, USA.

BGR. (2013). *Ackerbauliches Ertragspotential der Böden in Deutschland 1 : 1 000 000 (SQR1000). Digital map data v1 Hannover*. BGR. https://geoviewer.bgr.de/mapapps4/resources/apps/geoviewer

BGR. (2015). *Pflanzenverfügbares Wasser im Sommerhalbjahr in Deutschland 1:1.000.000 (GWN1000). Digital map data v1 Hannover*. BGR. https://geoviewer.bgr.de/mapapps4/resources/apps/geoviewer

Billari, F. C., Fent, T., Prskawetz, A., & Scheffran, J. (Eds.). (2006). *Agent-Based Computational Modelling*. Physica-Verlag HD. http://link.springer.com/10.1007/3-7908-1721-X

Brady, M., Sahrbacher, C., Kellermann, K., & Happe, K. (2012). An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services. *Landscape Ecology*, *27*(9), 1363–1381. https://doi.org/10.1007/s10980-012-9787-3

Chen, X., Viña, A., Shortridge, A., An, L., & Liu, J. (2014). Assessing the Effectiveness of Payments for Ecosystem Services: an Agent-Based Modeling Approach. *Ecology and Society*, *19*(1), art7. https://doi.org/10.5751/ES-05578-190107

Copernicus Land Monitoring Service - European Environment Agency. (2018). *CLC 2018*. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download

EEA, Schwaiger, E., Banko, G., Brodsky, L., & van Doorn, A. (2012). *Updated High Nature Value Farmland in Europe An estimate of the distribution patterns on the basis of CORINE Land Cover 2006 and biodiversity data*. https://www.eea.europa.eu/data-and-maps/data/high-nature-value-farmland

ESDAC. (2004). *Organic carbon content in the surface horizon of soils*. European Soil Data Centre, European Commission, Joint Research Centre. www.esdac.jrc.ec.europa.eu,

ESDAC. (2015). *Soil erosion by water*. European Soil Data Centre, European Commission, Joint Research Centre. ww.esdac.jrc.ec.europa.eu

Gilbert, G. N. (2008). *Agent-based models*. Sage Publications, Los Angeles, USA. https://dx.doi.org/10.4135/9781412983259

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

Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J., & Railsback, S. F. (2010). The ODD protocol: A review and first update. *Ecological Modelling*, *221*(23), 2760–2768. https://doi.org/10.1016/j.ecolmodel.2010.08.019

Habib, T. J., Heckbert, S., Wilson, J. J., Vandenbroeck, A. J. K., Cranston, J., & Farr, D. R. (2016). Impacts of land-use management on ecosystem services and biodiversity: an agent-based modelling approach. *PeerJ*, *4*, e2814. https://doi.org/10.7717/peerj.2814

Happe, K., Balmann, A., & Kellermann, K. (2004). *The agricultural policy simulator (AgriPoliS): an agent-based model to study structural change in agriculture (Version 1.0)* [Discussion Paper, Institute of Agricultural Development in Central and Eastern Europe, No. 71]. Leibniz-Institut für Agrarentwicklung in Mittel- und Osteuropa (IAMO). http://nbn-resolving.de/urn:nbn:de:gbv:3:2-22538

Janssen, M., & Ostrom, E. (2006). Empirically Based, Agent-based models. *Ecology and Society*, *11*(2). https://doi.org/10.5751/ES-01861-110237

Jones, R. J. A., Hiederer, R., Rusco, E., & Montanarella, L. (2005). Estimating organic carbon in the soils of Europe for policy support. *European Journal of Soil Science*, *56*(5), 655–671. https://doi.org/10.1111/j.1365-2389.2005.00728.x

Le, Q. B., Park, S. J., Vlek, P. L. G., & Cremers, A. B. (2008). Land-Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human–landscape system. I. Structure and theoretical specification. *Ecological Informatics*, *3*(2), 135–153. https://doi.org/10.1016/j.ecoinf.2008.04.003

Miyasaka, T., Le, Q. B., Okuro, T., Zhao, X., & Takeuchi, K. (2017). Agent-based modeling of complex social–ecological feedback loops to assess multi-dimensional trade-offs in dryland ecosystem services. *Landscape Ecology*, *32*(4), 707–727. https://doi.org/10.1007/s10980-017-0495-x

Mouratiadou, I., Lemke, N., Zander, P., Shaaban, M., Macpherson, J., Gaiser, T., Melzer, M., Hosseini-Yekani, S.-A., Niemann, N., Lingemann, K., Piorr, A., Helming, K., & Bellingrath-Kimura, S. D. (2021, September). *Digital Agricultural Knowledge and Information System: the DAKIS decision support platform for management design and ecosystem services provision*. Landscape 2021, Berlin-Online.

Müller, B., Balbi, S., Buchmann, C. M., de Sousa, L., Dressler, G., Groeneveld, J., Klassert, C. J., Le, Q. B., Millington, J. D. A., Nolzen, H., Parker, D. C., Polhill, J. G., Schlüter, M., Schulze, J., Schwarz, N., Sun, Z., Taillandier, P., & Weise, H. (2014). Standardised and transparent model descriptions for agent-based models: Current status and prospects. *Environmental Modelling & Software*, *55*, 156–163. https://doi.org/10.1016/j.envsoft.2014.01.029

Panagos, P., Borrelli, P., & Robinson, D. A. (2015). Tackling soil loss across Europe. *Nature*, *526*(7572), 195–195. https://doi.org/10.1038/526195d

Piorr, A., Ungaro, F., Ciancaglini, A., Happe, K., Sahrbacher, A., Sattler, C., Uthes, S., & Zander, P. (2009). Integrated assessment of future CAP policies: land use changes, spatial patterns and targeting. *Environmental Science & Policy*, *12*(8), 1122–1136. https://doi.org/10.1016/j.envsci.2009.01.001

Pohle, D., & Zasada, I. (2014). *CLAIM knowledge platform*. CLAIM Knowledge Platform. http://claimknowledgeplatform.eu/

Schwartz, C., Shaaban, M., Bellingrath-Kimura, S. D., & Piorr, A. (2021). Participatory Mapping of Demand for Ecosystem Services in Agricultural Landscapes. *Agriculture*, *11*(12), 1193. https://doi.org/10.3390/agriculture11121193

Shaaban, M., & Piorr, A. (2021, September). *Simulation of Dynamic Adaptation of Social-Ecological-System in Agricultural Landscapes*. Landscape 2021 - Diversification for Sustainable and Resilient Agriculture, Berlin-Online. https://doi.org/10.13140/RG.2.2.15013.42721

Shaaban, M., Scheffran, J., Elsobki, M. S., & Azadi, H. (2022). A Comprehensive Evaluation of Electricity Planning Models in Egypt: Optimization versus Agent-Based Approaches. *Sustainability*, *14*(3), 1563. https://doi.org/10.3390/su14031563

Shaaban, M., Schwartz, C., Macpherson, J., & Piorr, A. (2021). A Conceptual Model Framework for Mapping, Analyzing and Managing Supply–Demand Mismatches of Ecosystem Services in Agricultural Landscapes. *Land*, *10*(2), 131. https://doi.org/10.3390/land10020131

Squazzoni, F. (2010). THE IMPACT OF AGENT-BASED MODELS IN THE SOCIAL SCIENCES AFTER 15 YEARS OF INCURSIONS. *History of Economic Ideas*, *18*(2), 197–233. JSTOR.

Sun, Z., & Müller, D. (2013). A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models. *Environmental Modelling & Software*, *45*, 15–28. https://doi.org/10.1016/j.envsoft.2012.06.007

Tieskens, K. F., Shaw, B. J., Haer, T., Schulp, C. J. E., & Verburg, P. H. (2017). Cultural landscapes of the future: using agent-based modeling to discuss and develop the use and management of the cultural landscape of South West Devon. *Landscape Ecology*, *32*(11), 2113–2132. https://doi.org/10.1007/s10980-017-0502-2

Wilensky, U. (1999). *NetLogo* (5.3.1) [Scala]. Center for Connected Learning and Computer-Based Modeling, Northwestern University. http://ccl.northwestern.edu/netlogo/