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Embedding the integrated assessment of agricultural systems in a companion modeling process to debate and enhance their sustainability

Laure Hossard¹ · Caroline Tardivo^{1,2} · Jean-Marc Barbier¹ · Roberto Cittadini³ · Sylvestre Delmotte¹ · Christophe Le Page^{2,4}

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Abstract

The Companion Modeling approach aims to stimulate learning and sharing of perceptions among several actors through the co-construction and use of a model, while the Integrated Assessment of Agricultural Systems aims to assess a large set of performances of current and alternative systems. Our research question was: to what extent does the joint use of these two methods foster sustainability thinking? We show how the co-design of evolving agriculture scenarios and the use of Integrated Assessment of Agricultural Systems methods guided the implementation of a Companion Modeling process applied to the Valensole Plateau, southeastern France. An initial phase, based on a preliminary diagnosis, aimed to collectively formulate the issues to be addressed, and to engage the actors in a collective dynamic. The second phase consisted of leading actors in the co-construction of a simulation model to represent the agricultural system to be evaluated using economic, social, and environmental indicators at different scales. In the final phase, the current situation and the co-designed scenario were collectively analyzed. The scenario was conceived as a “worst case”, embedded with drivers such as input costs and climate change. Opposing adaptation strategies were envisioned by farmers and other actors. Results show how debates between participants adaptively shaped the model. Scenario simulations highlighted better environmental performance at the expense of economic performance. The differences between farms led to discussions on technical management. Overall, the process stimulated collective reflection among the actors and created a learning experience with the sharing of perceptions and knowledge about the agricultural system. The model was considered relevant by the participants, who expressed interest in continuing its exploration. Our approach, which used a unique combination of Integrated Assessment of Agricultural Systems and scenario development with Companion Modeling, could be adapted to other areas and issues, although tool transfer remains an open question.

Keywords Participation · Learning · Sustainability · Regional agricultural system · Sharing of representations · Scenarios · Multi-criteria evaluation · Multi-scale

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1 Introduction

Current debates in Europe have confronted the agricultural sector with a paradox: producing enough food to maintain low prices, while decreasing their impacts on the environment and human health. The spotlight on the environmental sustainability of agriculture has already led to numerous studies, tools, and approaches. While numerous conceptions of sustainability have been proposed (Zahm et al. 2015), Harwood (1990) defined it as “an agriculture that can evolve indefinitely towards greater human utility, greater efficiency of resource use, and a balance with the environment that is favorable both to humans and to most other species”. This definition highlights the three pillars of sustainability—environmental, social, and economic—which are present in most definitions (Zahm et al. 2015). Sustainability needs to be assessed at different yet interacting spatial scales: a field as part of a farm represents a structural component in a more complex landscape where some indicators and criteria (e.g., water quality, landscape diversity) are only fully evaluated at larger scales, while most farmers’ decisions and strategies are made at the scale of their farm and individual fields. Standardized tools and indicators have been developed to assess the sustainability of cropping systems (e.g., Reckling et al. 2016) or farms (e.g., IDEA, Zahm et al. 2015). But designing such generic tools at a landscape or regional scale is more difficult and often leads to a focus on specific issues or sector (e.g., sector-specific sustainability assessment tool in Coteur et al. 2018).

Recently, integrated assessment and modeling platforms have been built to simulate fine-scale interactions between water management and agricultural systems, leading to large sets of environmental, water management, and agricultural indicators of interest for actors (Allain et al. 2020). Such platforms, however, require large amounts of data that are not available through shared databases, and are time-consuming to acquire. Evaluation tools need to integrate several aspects in order to assess both the current situation and the consequences of changes in farming practices, which are difficult to test at large scale in situ (Legg 2004). Designing tools that allow for those changes and involve local stakeholders (farmers) and actors (e.g., advisers, cooperatives) can help in the development of common projections of future actions.

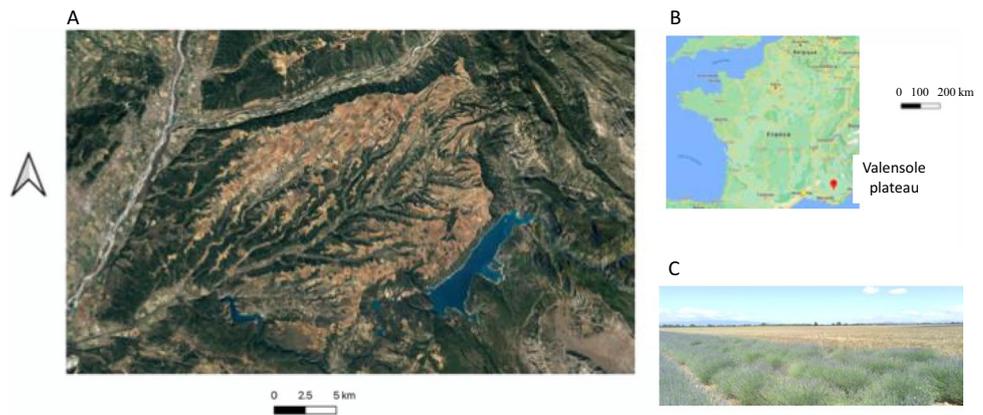
Different approaches have been proposed to stimulate collective exploration of agro-ecological systems through the use of models. Among them, the Integrated Assessment of Agricultural Systems (IAAS) is a systemic analytical approach aimed at exploring changes in the system (e.g., technical or organizational change, agri-environmental policies and prices) and assessing, ex-ante, their effects

on various indicators (e.g., production, income, nitrate leaching) at different spatial scales (van Ittersum et al. 2008), often using bio-economic farm models (Reidsma et al. 2018). IAAS is based on collaboration among disciplines, particularly with the objective of helping in policy decision-making. It recently integrated issues such as climate change (Paas et al. 2016). In other research, Companion Modeling (CM) is used to help heterogeneous groups of actors with different practices, strategies, and points of view, to collectively manage land and associated resources (Etienne 2011). This approach can be described as “transformative” modeling (Van Bruggen et al. 2019). While both of these approaches usually involve a combination of modeling and actor participation to explore different possible futures, they do not incorporate the two dimensions in the same way.

First, IAAS involves mechanistic models that are usually pre-existing (see, for example, Therond et al. 2009); sharing their development with actors is not key to the process, and this aspect can result in a lack of transparency in their role as tools for actors. By contrast, CM places the participatory design of the model at its core (“bottom-up model”; Barnaud et al. 2008), enabling it to reveal and formalize the actors’ perspectives (Le Page et al. 2015). Second, in most cases IAAS only mobilizes actors’ knowledge to design alternatives and does not mobilize participation at all stages, but CM regards the modeling process as a means to foster social learning. Third, CM is often focused on environmental issues (the state of resources to be shared/preserved), but generally a restricted set of indicators are used for evaluation (e.g., bushmeat hunting in Le Page et al. 2015), except in a few exceptions (e.g., Barnaud et al. 2008) where more sustainability dimensions have been studied. IAAS is structured around a systemic approach that can embrace agronomic, environmental, and economic indicators at different scales (e.g., Delmotte et al. 2017). Finally, while the more data-intensive IAAS is aimed at assessing quantitative comparisons of systems in order to guide policy decisions (e.g., Therond et al. 2009), CM is oriented towards actor negotiations and collective transformative learning (e.g., Le Page et al. 2015).

By taking advantage of their differences, Companion Modeling and Integrated Assessment of Agricultural Systems can be complementary: (1) CM can add participation that IAAS lacks by emphasizing the inclusion of actors and their roles, and model transparency; (2) IAAS can add emphasis from a systemic approach, with more complete and quantitative assessment than found in CM. In this study, we illustrate how we have combined the qualities of these two approaches to support a collective examination by actors on the sustainability of their agricultural system. It was developed at a regional scale on the Valensole Plateau, in South-eastern France (Fig. 1a, b). In this area, the sustainability of

Fig. 1 (a) Satellite image of the Valensole Plateau (Google Earth), (b) its location in France (Google maps), and (c) a typical landscape (lavender and wheat) (photograph by C. Tardivo).



agriculture is at the core of all actors' concerns, as the main cropping system (lavender-wheat, Fig. 1c) faces strong intensifying issues: a serious persistent disease (lavender decline), frequent droughts affecting wheat yields. These actors were thus looking for opportunities, such as the extension of the irrigation network. The objective of this study was thus to build a shared representation of the territory with the local actors of the Plateau de Valensole, in order to assess the sustainability of both the current agricultural system, and of alternative systems that would result from changes they expect to occur in the future. This work, which was built upon the co-design of a simulation model, was intensive, both in actor participation and in the collection and analysis of data (although no data pre-existed). As far as we know, this is the first time that methods and approaches of IAAS and participatory scenario design are based on a Companion Modeling approach.

2 Materials and methods

2.1 Overview of the method and participation

An initial evaluation of local agricultural systems was based on 24 interviews of local actors (Tardivo et al. 2014). Stakeholders interviewed first were identified in existing reports about the region. Other stakeholders were then included through a snowball sampling where each interviewee was asked to recommend other stakeholders. We stopped conducting interviews when no new stakeholder was recommended by the interviewees. This selection process led to the following diversity of profiles: 5 actors specialized in aromatic species; 2 in cereals; 2 in livestock farming; 1 in beekeeping; 7 in cropping systems; and 7 in territorial development. These 24 individuals represented a pool of expertise from which the participants to the subsequent workshops were selected. Our approach included five key tasks realized over the course of seven workshops and two additional series of interviews with

farmers. From three to twelve actors participated in each workshop (Fig. 2). They represented different types of knowledge (economic (e.g., cooperatives), environmental (Regional Natural Park), agronomic (farmers, Chamber of Agriculture, Administrations, Technical Institutes)), and specialization in the local crops (see Supplementary material 1 for details). We distinguished the regional scale for representatives working in regional development (i.e., Society for Irrigation and Regional Natural Park), as these representatives may have less detailed knowledge on the plateau, but represent a specific concern leading to potentially different points of view.

The overall approach began in 2013 (interviews of local actors), the workshops were held in 2014 (workshops 1 to 3), 2015 (workshops 4 to 6), and 2016 (workshop 7); farmers interviews were realized in 2014 (step 3) and 2015 (step 4).

2.2 Case study

The "Plateau de Valensole" is located in the NUTS-2 region, Provence-Alpes-Côte-d'Azur in southern France (coordinates 43°40'05"N–43°58'41"N; 5°47'06"E–6°17'32"E). It is a dry plateau, covering about 50,000 ha, with an altitude of 450 to 850 m. The plateau is bordered by surrounding valleys (Fig. 1a). Approximately a third of its area is covered by crops (15,500 ha in 2012), with lavender representing 22–24% of cultivated land (data for 2014 and 2010, respectively; source ASP, 2016). Lavender is mainly rotated with winter durum wheat (see typical landscape in Fig. 1c). Other crops are present (pea, rapeseed, sunflower, sainfoin, and sage) but represent a small part of the cultivated area. This low level of diversification can be attributed to three main factors. First, rainfall varies widely, with a yearly average of 656 mm per year, ranging from 408 to 893 mm per year (data Météo-France for 1996–2015, weather station of Valensole, altitude 600 m, coordinates 43°50'18" N 6°00'00"E). Second, soils are generally poor and shallow (40–60 mm). And third, there is not yet an organized market for the other crops.

	Tasks of the research	Methods	Participants Arom.; Cer.; CS.; Terr.; Total
1	- Formulation of a shared question	- Interview of 24 actors - Workshop #1	2; 2; 5; 3; 12
2	- Design of a conceptual model	- Workshop #2	1; 0; 4; 1; 6
3	- Design of a numeric model and the reference situation	- Workshops #3, #4, #5, #6 - Interview of 9 farmers	W#3: 2; 1; 1; 2; 6 W#4: 2; 1; 2; 0; 5 W#5: 1; 0; 5; 1; 7 W#6: 1; 0; 2; 0; 3
4	- Drivers of change and Scenario design	- Workshops #1, #6, #7 - Interview of 5 farmers	W#1: 2; 2; 5; 3; 12 W#6: 1; 0; 2; 0; 3
5	- Simulations and collective discussion on results	- Workshop #7	1; 1; 2; 2; 6

Fig. 2 Organization of the overall approach in five main tasks with associated workshops and participating actors. Actors are presented according to their professional role: specialists of Aromatic and Medicinal plants (Arom.), Cereals (Cer.), transversal to different

cropping systems (CS), or working in regional development (Reg, i.e., representatives of irrigation company, and Regional Natural Park, who were decision-makers). For tasks 3 and 4, the number of actors is indicated for each workshop (W#).

2.3 Formulating the question to be addressed by the approach and the model

During the initial interviews, each actor was asked to compose a question which he or she would like the participatory approach to address. To ensure that the question's form could be studied in the subsequent modeling approach, the actors were asked to follow a syntax which began with "What would happen if ..." or "What should be done for ..." Twenty-one individual questions were collected (3 of the actors interviewed did not formulate a question).

During the first workshop, these individual questions were presented to the actors, who commented, compared, and grouped them according to their common points (Fig. 3c). The actors were then invited to collectively formulate a shared question which would reflect the set of concerns raised by the individual questions. Among the twelve actors who participated in this workshop, four were new to the process and therefore had not contributed to the initial evaluation. Note that these new participants (representatives of already interviewed companies or institutes), as well as the ones who previously formulated a question, could formulate new ones. Participants found that the questions presented covered the main issues of the territory.

The shared question produced in this first collective activity was aimed at identifying a clear, shared objective for

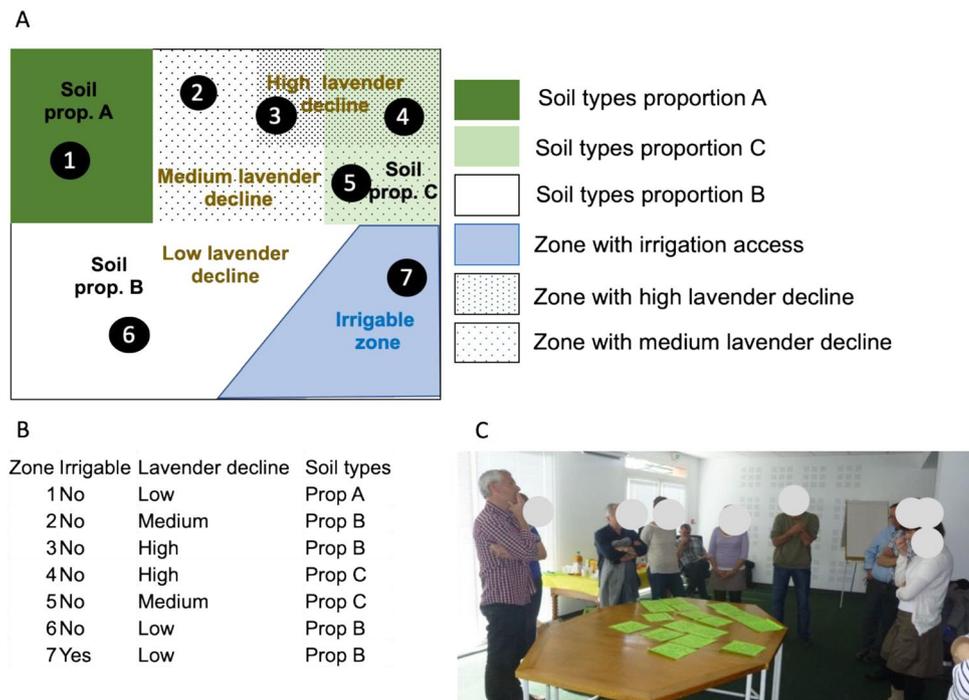
the implementation of the approach. As the first object co-constructed with the region's actors, this question formed the base on which to launch the dynamics of a collective reflection on the sustainability of the agricultural system on the Valensole Plateau.

2.4 Building the conceptual model

The conceptual model was co-built with actors during the second workshop and represents the main components of the agricultural system and the relationships between those components.

Cognitive maps developed during the initial interviews and evaluation identified 37 potential components of the agricultural system (Tardivo et al. 2014). These components were related to farm types, sectors, cropping systems, natural resources, actors, and infrastructures (distilleries, irrigation networks). During the second workshop, they were presented to the 6 participating actors (Fig. 2) who used the shared question developed in the first workshop as a basis to select five components that they considered most important to the conceptual model's representation of the system. In the process, the actors were allowed to reformulate components, merge them, or add new ones. The relationships between the selected components were then identified: the participating actors used a keyword to explain the relationship between

Fig. 3 (a) Schematic representation of the Valensole Plateau in seven zones and (b) its summary, (c) co-designed with local actors during the modeling process (photograph by C. Tardivo).



components. Finally, the conceptual model was discussed and collectively adjusted for internal consistency (Fig. 5).

2.5 Building the numerical model and the reference situation

2.5.1 Modeling approach

As in most CM approaches, we developed a simulation model where elements are spatially represented. In combination with qualitative research methods (interviews, workshops, etc.), this type of modeling makes it possible to engage stakeholders in an adaptive approach, where the model can evolve together with their perceptions during the exchanges that take place in the participatory workshops (Etienne 2011).

The numerical model, based on the conceptual model, is aimed at representing reference situation: (1) the representation of spatially unique characteristics (irrigable area, soils, and zones of lavender in decline; Fig. 3a, b), (2) spatial distribution of typical farms, (3) farm activities accordingly to type, and (4) climate. Using these four sets of information as inputs, the numerical model is also aimed at (5) assessing the performance of the reference situations through the use of co-specified indicators (outputs) defined at different spatial scales. These five sets of information were co-designed with the actors participating in the workshops, with some elements retrieved from farmers' interviews and some other ones from existing databases that were provided or suggested by actors.

The numerical model was implemented using the Cor-mas platform (Bousquet et al. 1998), based on a conceptual model that was formalized using the Unified Modeling Language (UML). The central part of Fig. 4 shows the UML class diagram, with the main entities of the model as rectangular boxes (irrigation in blue; spatial entities in orange, type of crops and vegetation in yellow, and climate in green). Performances are determined for each crop depending on climate, irrigation, its cropping practices, and its location (agro-ecological zones), and then upscaled to farm, zone, and landscape level.

2.5.2 Agro-ecological zones

The spatial dimensions of the model were defined over the course of four workshops (workshops 3 to 6), with progressive iterations leading to changes for soil representation in particular. To begin (workshop 3), the researchers proposed to the actors a schematic rectangle as a representation of the territory of the Valensole Plateau, inspired by the real shape of the territory (Fig. 1a). It also included an initial proposition for the spatial representation of an irrigable zone and one representing the intensity of decline in the lavender crop. This proposition served as a basis for interactions during the workshops.

2.5.3 Typical farms and their spatial allocation

The farm typology was built in workshops 3, 4, and 5. Researchers developed a beginning proposal based on the

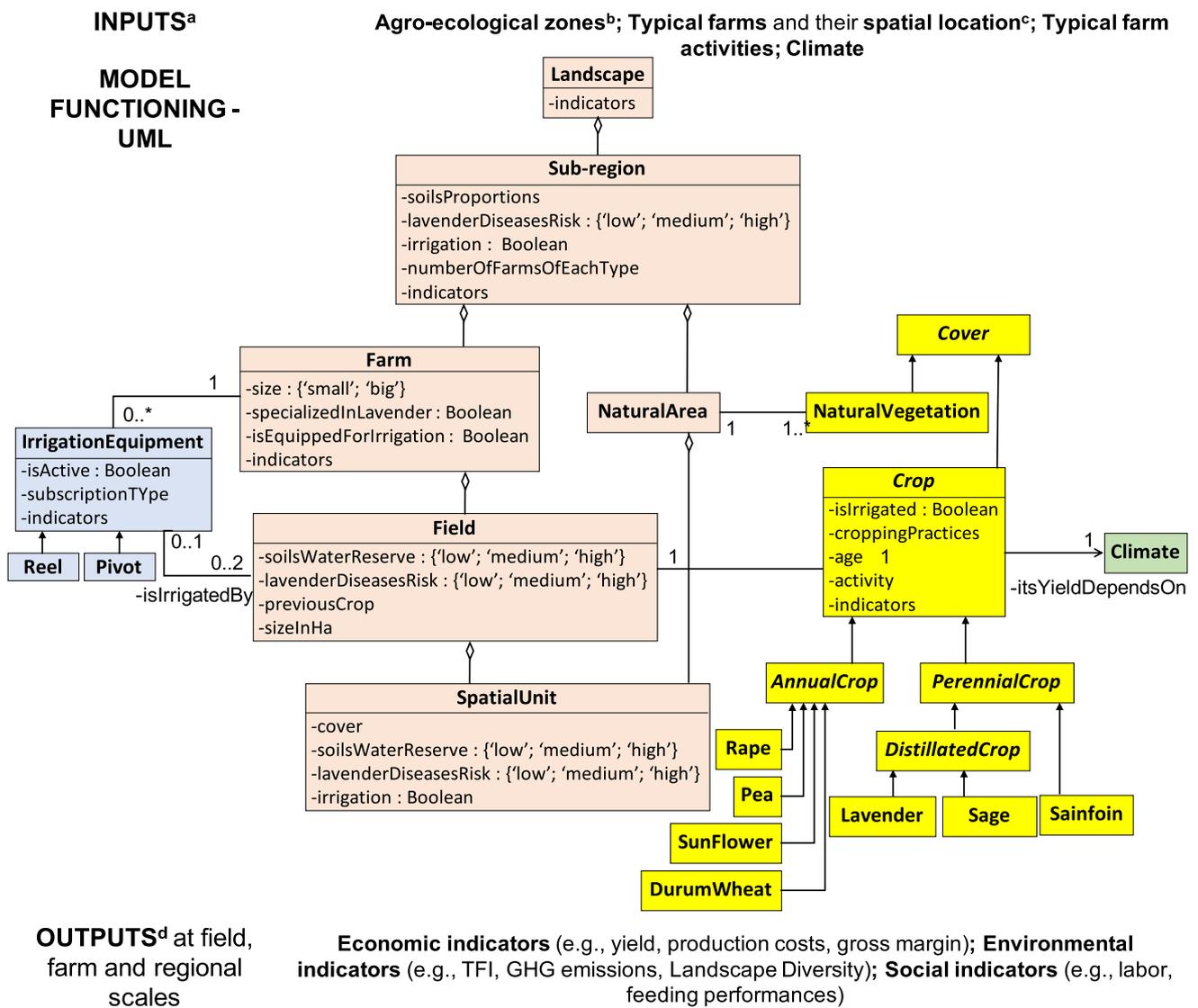


Fig. 4 Inputs, ULM diagram, and outputs of the developed model. ^aAll inputs are initially defined for the reference situation, and can be changed in the scenario; ^bAgro-ecological zones are presented in Fig. 2a, b; ^cThe spatial location of a typical farm is presented in Sup-

plementary material 2; ^dThe complete list of indicators, and associated formulae, is presented in Supplementary material 3. TFI: Treatment Frequency Index; GHG: greenhouse gas emissions.

initial farmers’ interviews and evaluation (Supagro, 2013). Farm typology changed in the successive iterations, becoming more precise in terms of three main criteria: farm size, degree of specialization in lavender, and equipment for irrigation. At the actors’ request, this work was also based on CAP (Common Agricultural Policy) declarations from 2012, particularly regarding farm sizes to be represented in the model. To obtain CAP European subsidies, each farmer has to yearly make a declaration of his surfaces and the associated crops. These declarations are performed on a map. Considered over a region, declarations thus allow having the number of farms, their crop surfaces and locations, and the size of each farm.

For irrigation equipment, the UAA (utilized agricultural area) that can be irrigated by one roller was based on previous studies (Supagro, 2013). Spatial allocation of typical farms was based on CAP data (see the result in Supplementary material 2). In the model, each farm was represented with 10 fields in order to facilitate the representation of the different crops in a year (% of each crop rounded to 10%).

2.5.4 Farm activities

The objective was to define the reference situation for each farm type in each zone in terms of crops, crop sequences, technical management, and associated performances (yield,

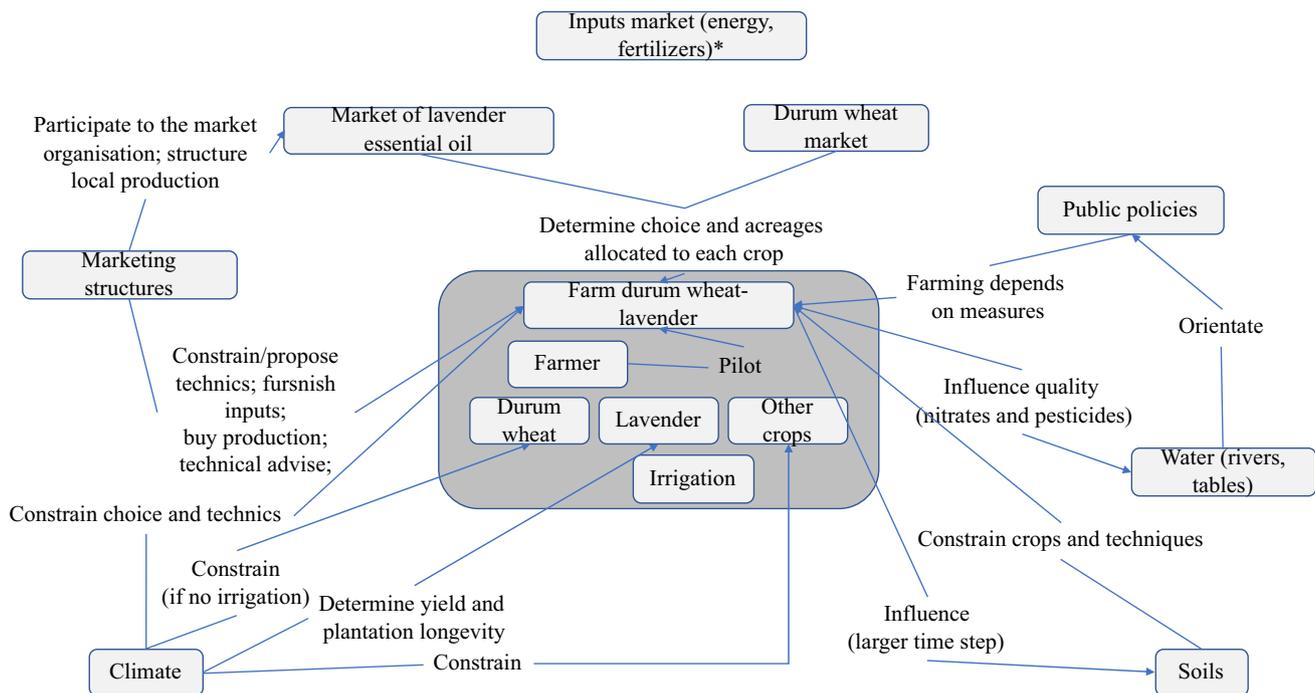


Fig. 5 Conceptual model built by the participants during the second workshop. In dark grey are indicated the farm (internal) components; in light grey are indicated the external components that constrain/permit farmers' choices. *As it was selected at the end of the work-

shop, its relationships with other components were not detailed. As presented in the farmers' adaptations (section 3.4), it was used as a driver for farm choice for crops and their acreages, and to calculate economic performances.

costs, etc.; see indicators in Supplementary material 3). Farm activities (crop sequences and associated technical management) were specified and validated using different types of data: previous interviews of farmers in the same area (Supagro, 2013), CAP data from 2012, interviews with farmers in tasks 3 and 4 (Fig. 2), and information gathered in workshops 5 and 6.

Cropping systems were determined by considering eight criteria successively. The first two were related to the co-designed spatial characteristics of the seven identified zones (Fig. 3a, b): possibility of irrigation; and longevity of lavender plantations resulting from the soils and decline intensity. This produced a mean longevity at farm scale for the different zones. We then mobilized CAP data to calculate the relative UAA for lavender in each zone. This information was used to calculate the number of years between two lavender cycles. Using both CAP data and farmers' interviews, we listed the crops grown in addition to lavender and durum wheat. This information was integrated to compute manually all possible rotations. Adding the relative acreage in wheat (from CAP data), we computed two types of rotation, one with lavender and the other without (consistent with farmers' interviews), for

each farm type. Rotations were programmed as close as possible within the UAA in lavender and durum wheat, while respecting agronomic rules cited by farmers (e.g., lavender is always planted after wheat, wheat is always grown after lavender, wheat is grown maximum two successive years; see Supplementary material 4 for more details). The length of the simulation (48 years) chosen for the model depended on the numerous possibilities for rotations, including semi-perennial crops (up to 13 years for lavender, and 3 years for sage).

2.5.5 Climate

Most of the discussions on current climate characteristics took place during workshop 5.

Although the Valensole Plateau experiences different types of climatic variation (e.g., frost, autumnal droughts), actors decided to consider climate variability in terms of spring rainfalls only (workshop 5). Three levels were defined: a dry spring with less than 50 mm of cumulated rainfall, a rainy spring with more than 100 mm of cumulated rainfall, and a medium one with values in-between. These values were based on climate data and the expertise of one

participant, and were validated by the actors in workshop 6. The reference situation used to define the baseline scenario only included medium rainfalls, while the future scenario used a dry spring every 4 years (due to the climate change effects present in the scenario designed by the stakeholders, see section 3.4).

2.5.6 Indicators

An initial proposition was developed by researchers based on the conceptual model and beginning evaluation. Based on this proposition, indicators were iteratively discussed and modified over the course of workshops 3 to 6. Indicators addressed economic (yield, production, gross margins considering production costs and subsidies, labor) and environmental performances (two indicators for pesticides, greenhouse gas emissions, and energy consumption) at field and farm scales. For subsidies, we considered the CAP framework of 2003–2013 (single farm payment, coupled aids for a few crops) for the reference situation, and the framework of 2014–2020 (basic payment, greening payment, coupled aids for a few crops, redistributive payment) for the scenarios (consistently with the narrative designed by the actors, see section 3.4). Details on subsidies are presented in Supplementary material 5.

At the territorial scale, three indicators were examined: landscape diversity, proportion of lavender for each spatial zone (as a proxy for apiculture, suggested by a participant), and feeding performance. Feeding performance is expressed in persons fed for a year by the local production, considering only energy content (MJ). Information to compute indicators were gathered from literature, previous data (Supagro, 2013), and interviews with specific farmers (see Supplementary material 3 for the complete description of indicators).

2.6 Scenario design

Scenarios are defined as “descriptions of possible futures that reflect different perspectives on past, present and future developments” and include the description of an initial situation and the driving forces that might cause a specific future (Alcamo and Henrichs, 2008).

In this study, the design of scenarios was achieved in four main steps over the course of three workshops (1, 6, and 7) and included interviews of farmers between the final two workshops (Fig. 2). Scenarios were designed to present alternatives that would be assessed by the numerical model. The time step of 15 years was chosen in conjunction with the actors. Scenarios could consider changes of each model input, as presented Fig. 4.

The drivers of change were listed (first step) by the 12 actors during the first workshop. After no new idea emerged, each participant selected the three most probable

and important for him (i.e., the ones that appeared to him as having the most important consequences on agricultural systems). During the sixth workshop, the actors completed the second step, building an exploratory, narrative scenario based on the list and ranking of drivers. Since no farmer was present at this sixth workshop, the projections of possible farm adaptations to these changes were not complete. Therefore, in a third step, five farmers (of different farm types) were individually interviewed to obtain their perspective on the probability of such changes occurring and to confirm and refine the adaptations they would anticipate when facing such changes. These adaptations were simulated in a scenario called “Farmers’ adaptations.” The fourth step then took place during workshop 7, in which actors discussed the outputs achieved from running the model with the co-constructed scenarios (baseline, and “Farmers’ adaptations”). During this last workshop, actors suggested other adaptations for farms, which were ultimately simulated with the model. This scenario is thereafter presented as “Actors’ adaptations.” These two scenarios, which share the same drivers but differ in their adaptations, were simulated.

3 Results and discussion

3.1 Common question to address

The individual questions from the initial interviews were diverse, but the majority corresponded to three main themes: irrigation (two questions mentioned by seven actors in total), farm profitability (eight questions), and environmental impacts of farming (four questions). Two questions diverged from the major themes (one related to diversification, the other one to the installation of young farmers). Questions on irrigation focused on the consequences of extending the irrigation network, and how this should be developed. Questions on farm profitability were more varied, focusing on consequences from numerous possible changes: spatial expansion of lavender decline and subsequent decrease in acreages, CAP reform, increases in energy costs, and decreases in rainfall. Questions about the environmental impacts of agriculture were related to biodiversity (how to recover it), water quality, and nitrate pollution.

During the second workshop, the shared question was formulated: “What would a sustainable future look like for farms on the Valensole Plateau?” The actors also wanted to add a sub-question: “How can farmers improve production systems on the Valensole Plateau?” This second question directs the first one towards ways to improve the current production systems of the Valensole Plateau.

The notion of sustainability allowed the actors to formulate a consensual question that could encompass the variety of issues addressed in the individual questions.

Interdependencies among these issues were frequently discussed during the formulation process, and attempts by some actors to focus the question on a more specific theme or issue were unsuccessful. The farm, seen as a decision-making unit subject to various changes affecting its performance, proved to be the key element for investigating ways to improve production systems. The assessment of sustainability was focused on agricultural activity; other activities and the region's natural phenomena were seen as secondary.

This focus on sustainability without referring to any specific resource is unique compared to most other CM studies. For example, Souchère et al. (2010) focused on risks of erosive runoff. Barnaud et al. (2008) focused mainly on erosion and water problems, and Le Page et al. (2015) focused on bushmeat hunting.

3.2 Conceptual model

Top-ranking components were “lavender-wheat-based farm,” “lavender,” “wheat,” “other crops,” “European Union,” “Climate” (each cited in 9 cognitive maps), “Irrigation” (8), “soils” (7), and the markets of “durum wheat” and “lavender oil” (6 each). All these components were integrated in the conceptual model, although actors reformulated some of them (e.g., “European Union” became “Public policies”) (Fig. 5).

The final conceptual model includes 14 components (Fig. 5). Only the farms primarily cultivating lavender and durum wheat appear in this conceptual model, placing an initial limit on the general question. In addition to these two primary cultures, the actors mentioned “other crops,” but did not consider it useful to identify them at this stage of the process. Irrigation was mentioned at the farm scale, because actors saw it from the perspective of its impact on crop performance and its position as an element managed by the farmer.

Two sectors of agricultural production shape the conceptual model (Fig. 5): lavender essential oil and durum wheat. These two sectors have a direct influence on the farm, since they determine the choice and proportion of crops at farm scale. The input market (energy and fertilizers) was added to the conceptual model to take account of price variations in future scenarios. Since it was added at the end of the workshop, its relationships with other components of the model were not clarified.

Public policies were considered because of their influence on farm performance and farmers' strategies. Finally, climate also appeared in the conceptual model and it impacts are differentiated according to the crop. For instance, climate affects the yields and protein quality of durum wheat and the yields and longevity of lavender plantations. Direct constraints on the farm, via the choice of crops and technical management by the farmer, were also made explicit. The

influence of agricultural activity on soils and water in rivers and groundwater were specifically highlighted. In terms of soil, this influence takes place over a longer period and is reciprocal, since the quality of the soil can condition the choices of crops and technical management.

Although it corresponds to the formulated question, this model can be viewed as being oriented towards agriculture when compared to the wide range of elements involved in sustainability. Its structure depends strongly on the participants (no actor working on regional resources was represented, Fig. 2). However, we tried to limit this bias by making available all the components that were cited in the individual interviews. This type of participation bias has already been highlighted in previous studies (e.g., Barnaud et al. 2008).

3.3 Simulation model

3.3.1 Agro-ecological zones

In workshop 3, the actors were shown a schematic representation of the region, including the delineation of two zones of intensity of lavender decline, and a delineation of water access. While actors agreed with the depiction of water access, they decided to add an intermediary zone of decline intensity (Fig. 3a). They also spatially distinguished two zones of the plateau, one with low forest cover in the North and one with high forest cover in the South, but in the following workshop they decided not to keep this distinction. This change should be seen as part of the dynamics in participation: the regional actor (Natural Regional Park) who suggested this modification was absent in the following workshop. However, the same participant did not revisit the forest delineation when rejoining the discussion in the next workshop.

The first delineation of soil types was produced in workshop 4. It identified three zones based on water storage capacity, which corresponded to those of decline intensity. This representation was rejected in the next workshop by participating farmers. They pointed out that this representation did not take account of the significant heterogeneity in soils that is observed both at the scale of the plateau, and at finer scales (e.g., a single field). They suggested a new configuration, based on a south-west/north-east gradient, where each spatial unit (field) would have a probability of low, medium, or large water storage capacity. It is worth noting that the participant who initiated the first soil representation, in workshop 3, did not participate in workshop 4. The actors who were present in both of these workshops gave little attention to this topic during workshop 4.

Given the uncertainty in terms of soil representation, the researchers decided to use a soil type map that was built by the institute of one study participant, together with the

expertise of this participant. This led to three classes of water storage capacity (WSC): higher than 75 mm (high), lower than 50 mm (low), and the values in-between (medium). These classes are represented throughout the plateau, so researchers proposed to delineate zones where these three classes have different proportions. The western area of the plateau's schematic representation was composed of 53% high, 30% medium, and 17% low WSC (designated as proportion A). The central area included 20%, 50%, and 24% of high, medium, and low WSC (proportion B). The eastern area was composed of 8%, 33%, and 28% of high, medium, and low WSC (proportion C). Note that for the central and eastern areas, the map presented zones where WSC had not been determined. We thus mobilized other soil data (Revel-Mouroz, 2013) to complete the soil map.

This soil type representation was proposed to the actors in workshop 6. The final soil spatial representation (Fig. 3a) reflects their modification, reducing the spatial extent of soil types with proportion A. The final soil representation depicts WSC in high, medium, and low, proportions: type A proportions of 50% high, 30% medium, and 20% low; type B of 20%, 50%, and 30%; and type C of 40%, 30%, and 30% (Fig. 3b).

Soil representation drew the most attention in discussions over spatial elements and accentuated the differences between participants with a more global vision and those who typically confront soil diversity at a smaller scale. The final representation was able to accommodate the concerns of all actors, highlighting the advantage of an iterative process, together with the mobilization of external data that was analyzed at the request of actors. This type of combination can help to reduce uncertainties associated with single sources of information (Reed, 2008).

3.3.2 Typical farms and their spatial allocation

The structural typology of farms is based on three distinguishing criteria: (i) utilized agricultural area (UAA), leading to medium or large farms; (ii) level of specialization in lavender, specialized or non-specialized farms (determined by a threshold of 35% of UAA in lavender); (iii) irrigation equipment (equipped or not).

The decision not to consider a small farm type was related to the approach targeting the lavender-durum wheat production system; this choice was validated in workshop 3. The final determination of typical farm sizes was based on CAP data of 2012 (see section 2.5.2 for details). This method was suggested by actors in workshop 4 and took place in two stages. First, we considered the mean size of all farms that are located on the plateau and make a declaration to CAP (82 farms with an average size of 100 ha). We divided the farms in two groups according to this threshold (below vs.

above 100 ha for medium and large farms, respectively). This threshold was validated in workshop 5. We then determined the size of the typical farms, medium and large, by calculating the mean of each group, resulting in a medium farm with UAA of 60 ha and a large farm of 160 ha. The actors believed farm size would influence farming systems, and technical and economic results; it would also affect their adaptive capacities and development opportunities. Equipment depreciation expenses were frequently cited as an explanation for these differences: medium-sized farms would have higher equipment depreciation expenses per hectare than large ones. In addition, large farms are said to use less labor per unit area than the average (there are few permanent workers on the Valensole Plateau).

Actors in workshop 5 suggested distinguishing farms according to their degree of specialization in lavender. This degree of specialization was formulated as the portion of UAA devoted to lavender. The first estimate was 20% of UAA in lavender, but the actors asked researchers to base the calculation on CAP data, leading to a final 35% threshold distinguishing between non-specialized and specialized farms. Actors felt that the level of specialization in lavender would strongly influence the revenue structure and condition the strategic choices made by farmers. Indeed, lavender is currently an important source of income but requires significant labor, especially in distillation and planting. The farms specialized in lavender would tend to simplify the technical management of cereal crops in order to leave as much time as possible for their lavender crops. They would also be less inclined to diversify the crops in rotation with lavender.

Two types of irrigation equipment were considered by actors in workshop 3. During workshop 6, further discussions limited the typical irrigation equipment to lateral-roll systems. The determination of UAA that can be irrigated by one roll system was based on previous studies (Supagro, 2013).

While farm size, orientation, irrigation possibilities, and soils correspond to a classical way of categorizing farms in IAAS (e.g., Delmotte et al. 2017), the spatial representation was used to allocate farm types across the plateau. This pushed the typology to include more space-related elements (e.g., lavender decline intensity) and to describe additional farm characteristics. Spatial representation is at the core of CM simulation models. However, specific farm types are rarely distinguished or characterized in detail. Barnaud et al. (2008) identified three farm types according to their size and strategies; the farm types were differentiated in the model by different levels of land, capital, and family needs. In this study, we have focused less on social aspects and more on the agricultural issues and factors constraining production (e.g., soils, material and labor, irrigation possibilities, and intensity of lavender decline).

3.3.3 Farm activities

The crops considered included lavender, durum wheat, sage, rapeseed, pea, sainfoin, and sunflower. Their proportions differed generally according to zone and soil WSC. But they also differ between the typical farms: specialized farms do not grow pea or sunflower crops; non-specialized farms and medium specialized farms do not grow sage. Depending on the WSC, irrigation, and intensity of decline, lavender crops were defined as lasting from 6 to 13 years.

In terms of crop management, simplified cultivation techniques are used to save labor only in some farms. Those are the large farms (material is too costly for medium farms), which are non-specialized in lavender (specialized farms are less interested in annual crops' management). This type of crop management is considered in the model for fields where lavender is never grown (i.e., rotation without lavender), for wheat, pea, and rapeseed. Apart from these elements, no clear distinction in technical management could be made between typical farms. Detailed characterization of cropping systems (rotations and technical management) in farm typologies is systematic in IAAS, but rare in CM approaches.

3.4 Co-designed scenarios

The drivers most often cited by actors in workshop 1 concerned global changes (Table 1), and most of them had already been highlighted during the preliminary evaluations and the formulation of the individual questions. This was the case, for example, of an increase in the occurrence of

extreme weather events, and in particular droughts (spring or autumn). Changes in the markets, such as a significant fall in the price of lavender essential oil, were also considered important. Demand might change for certain productions, such as an increase in demand for clary sage, thus generating new opportunities for diversification. Rising energy prices, which would increase the costs of fertilizing durum wheat and distilling lavender, were a concern. Tightening of national and international regulations were also mentioned, both for the use of phytosanitary products and for that of nitrogenous fertilizers. The potential classification of the territory as a nitrate vulnerable zone could result in a ban on the autumn application of nitrogen fertilizers on durum wheat, and in turn, cause yields to fall. The actors also mentioned the risks of banning currently authorized phytosanitary products because previous bans had significant consequences on lavender yields. The reform of the CAP was underway at the time, and its main objectives were known (such as the principle of convergence and greening). However, its consequences on farm economics remained very uncertain, as were the adaptations that might then be initiated by farmers. At the local level, two main changes were mentioned: the extension of irrigation and the progression of lavender decline. Finally, two technical drivers were also mentioned: the improvement of simplified cultivation techniques and of organic matter management (Table 1).

Based on this list and ranking of drivers (Table 1), actors in workshop 6 built a narrative scenario focused on the evolution of changes in the global context, with four main drivers: prices and costs, nitrate regulation, climate change, and

Table 1 Drivers of change cited in workshop 1 as being important in a time horizon of 15 years; frequently cited are indicated with +. CAP Common Agricultural Policy; REACH regulations concerning the registration, evaluation, and authorization of chemical substances, as well as the restrictions applicable to these substances; CUMA Cooperative Use of Agricultural Equipment.

	Citation frequency
Global drivers of change	
Increase in the occurrence of extreme weather events	+++
Fluctuation in production prices and changes in demand	+++
Tightening of national or European regulations on nitrogenous fertilizers	++
Evolution of national or European regulations on plant protection products	++
Changes in energy prices	++
New CAP reforms	++
Implementation of REACH regulations (tightening of the technical obligations of distillation)	
Local drivers of change	
Geographical extension of the irrigation network	+++
Progression of lavender decline	++
Increased soil erosion	+
Collective organization of farmers (e.g., CUMA)	+
Implementation of policies favoring the installation of young farmers	
Designation of spaces reserved for tourism	
Technical drivers of change	
Improvement of simplified cultivation techniques allowing higher yields to be obtained	+
Development of new organic matter management systems	

policy. This scenario considered price changes, with lower prices for lavender essential oil (drop from 19€ to 15€), and higher costs for chemical inputs (increase by 2 to 4% each year). It also included the consequences of classification in a vulnerable nitrate zone, with nitrate regulations prohibiting nitrogenous fertilizers spreading in autumn, resulting in consequences for technical management and the yields obtained (especially for durum wheat). Another important driver was climate change, with a higher frequency of droughts. There are spring droughts, reducing the yields of all crops, and autumn droughts, leading to premature plant death in parts of lavender fields. At the same time, the CAP reform leads to an increase in the cultivated area of the most profitable crops.

Some farm adaptations were also mentioned but were not detailed enough to be simulated. To design these adaptations, five farmers were interviewed (Fig. 2). According to our farm categories, they all had large farms, only one had irrigation, two were specialized in lavender, and all were located in soil types B and C. Two of the five interviewed farmers had their plots in the high lavender decline zone, two in the medium lavender decline zone, and one in the low lavender decline zone.

Scenario “Farmers’ adaptations” Using this global narrative, i.e., the narrative designed by actors in workshop 6, the five interviewed farmers showed how they would adapt their farm’s cropping systems and technical management under these changes. They all felt such changes were coherent for the time horizon of 15 years. Subject to these changes, farmers would adapt their crop acreages in different ways. The interviewed farmers who were already specialized in lavender would increase the area of lavender cultivation because they felt that it would remain more profitable than other cultivated species, despite the problems encountered (worsening of decline, droughts, lower prices). From their perspective, increasing the area of lavender would make it possible to maintain farm income. In an opposite strategy, the interviewed non-specialized farmers would decrease their lavender area and diversify their system with crops such as rapeseed, sunflower, or pea. According to these farmers, making the farm less dependent on the cultivation of lavender would reduce vulnerability to the growing risks of lavender decline, drought, and falling prices. All farmers mentioned an increasing need for renewal of lavender plantations (as soon as 4 years after planting) because of the rapid crop yield decline due to lavender disease. They mentioned adaptations in technical management: changing the herbicides used on lavender or using simplified cultivation techniques for other crops in order to reduce input and fuel costs, and the use of organic fertilizers to cope with regulations relating to the classification as a nitrate vulnerable zone.

The adaptations mentioned by farmers were thus in two opposite directions: specialized farmers would increase their area with lavender, while non-specialized farmers would diversify more, and decrease their area without lavender. We thus called the farmers’ adaptation scenario “Opposite strategies scenario.”

Scenario “Actor’s adaptations” The opposing strategies, designed by farmers under the narrative built by actors, and their evaluation with the model were presented to actors in workshop 7 (mainly non-farmers), who perceived the main components to be plausible and relevant. However, they questioned the adaptations modeled for the typical non-lavender farms (i.e., reduction in lavender area and diversification).

These actors suggested that a more logical adaptation to the changes included in the narrative scenario would be for the non-specialized farms to increase their lavender areas, just like the specialized farms. Indeed, the gross margin of this crop, although reduced, remained significant in this scenario. As with typical lavender-specialized farms, an increase in lavender surface area would therefore partially offset the decrease in gross margins for the various other crops. Thus, all farmers, whether specialized or not, would increase their area with lavender, i.e., they all would go for more specialization. We thus called the actors’ adaptation scenario “Specialization scenario.”

This led to the simulation of the two scenarios that share the same drivers but differ in terms of adaptations for farms that are not specialized in lavender: Scenario “opposite strategies,” and Scenario “specialization.” There were different rotations according to the scenario and the farm type (specialized/non-specialized in lavender; medium/large size), and in the areas they represent in each farm type (Supplementary material 6). These simulations also involved other changes in the model, such as climate, prices, zoning, and technical management (Supplementary material 6).

Interestingly, actors did not focus on the extension of irrigation in the scenarios even though it was at the core of the discussions at the beginning of the participatory approach. The scenario considered climate change as a driver (more droughts), and it was supported by one participant who works for an irrigation company. Such a shift was probably affected by the process’s time and participation dynamics (i.e., the representative of the irrigation company was absent when the narrative was built, see Supplementary material 1), which in a CM approach, are at the core of model building and exploration (Etienne 2011).

The unique aspect of our final scenario design was the combination of actors and farmers to agree on a possible future and then propose a coherent set of anticipated drivers and design adaptations. The contrast between opinions of the farmers and those expressed by the managers in the last

workshop showed the discrepancy between these two types of actors. The limited involvement of farmers in parts of the project does question the dynamics of the participation.

3.5 Results of simulations

In the reference situation, large variations in performance were observed between crops (Supplementary material 7). For example, lavender and sage had the highest mean gross margin (1274 and 1349€/ha, respectively), while winter wheat and sunflower showed the lowest (555 and 28€/ha, respectively). The highest average production costs were for sunflower and lavender (> 650€/ha), and the lowest were for pea and sage (< 300€/ha). Lavender's high production costs were partly linked to distillation (18% of total costs) and labor; for sunflower, the high costs were due to input and seed costs. The lower production costs for pea were linked to the absence of nitrogen fertilization, which represented 48 to 70% of total costs for the other crops. In terms of pesticides, lavender presented very high values for both TFI and EPPI; sage ranked second for both. Energy consumption and GHG emissions were the highest for winter wheat, and the lowest for pea; lavender and rapeseed also showed high values (> 15,500 MJ/ha and > 1400 TeqCO₂/ha, respectively, on average).

In the reference situation, the two main crops were winter wheat and lavender (28% and 34% of the regional UAA, respectively; Fig. 6a). The area dedicated to lavender

increased (51%) in the “specialization” scenario, but it decreased (31%) in the “opposite strategies” scenario, leading to more crop diversification in the latter.

The performances at the regional scale are presented in Fig. 6b. All performances were maximum in the reference situation, except for labor, where the “specialization” scenario ranked first (due to more labor for lavender plantation and distillation). The average gross margin at the regional scale, which is 873€/ha in the reference situation, fell to 528€/ha and 602€/ha for the “opposite strategies” and “specialization” scenarios, respectively. This decrease in the gross margin is due to both the decrease in lavender price, and the increase in input costs (Supplementary material 6). The indicators of environmental performance (whose decrease could be desirable), all decrease in the two scenarios, as compared to the reference situation. New TFI values for the scenarios were less than 80% of the reference situation, and values for EPPI were less than 66% of the reference. Energy consumption and greenhouse gas emissions were 88% and 66% of the reference values (Fig. 6b). Part of these improvements is due to simplified techniques, which require less use of machinery.

Reducing the scale to the typical farms highlighted differences between farms specialized in lavender (Fig. 7a, b) and those non-specialized (Fig. 7c and d). For example, we can see the different percentages of crops, and gross margins in the reference situation of 1015 and 785€/ha for specialized and non-specialized farms, respectively. Note that for specialized farms, the adaptations are similar for

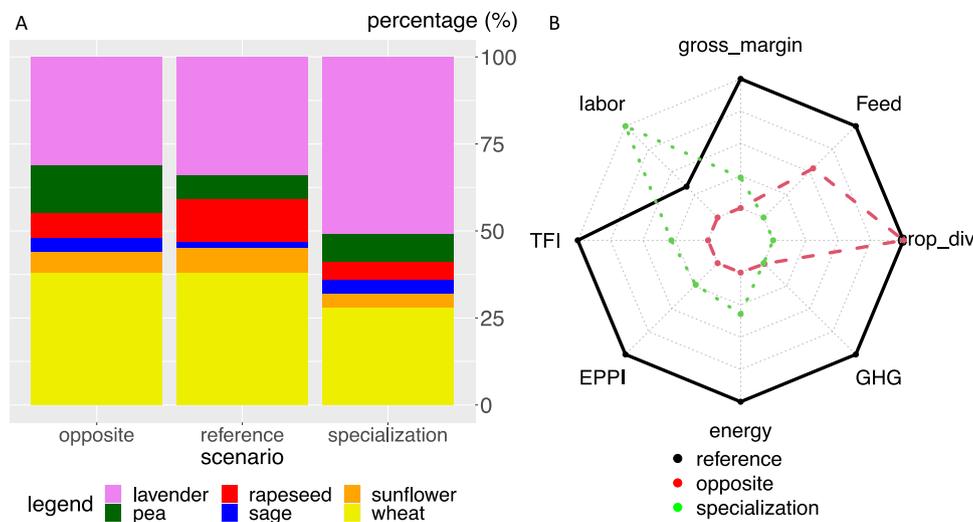


Fig. 6 Results of the simulations for the reference, “opposite strategies,” and “specialization” scenarios, in terms of (a) cultivated crops and (b) performances, for an average regional hectare. The gross margin is expressed in €/ha (min=517.8; max=873.5); Feed corresponds to the feeding capacity, in persons per year (min=38.9; max=68.2); Crop_div corresponds to the diversity in crops, unit-

less (min=0.75, max=0.82); GHG to greenhouse gas emissions, in TeqCO₂/ha (min=1526 and max=1850); energy to energy consumption, in MJ/ha (min=12,791; max=15,093); EPPI to Environmental Phytosanitary Pressure Index, unitless (min=1.6; max=2.9); TFI to Treatment Frequency Index, unitless (min=2.3; max=3.2); labor is expressed, in hours/ha (min=7.27; max=8.54).

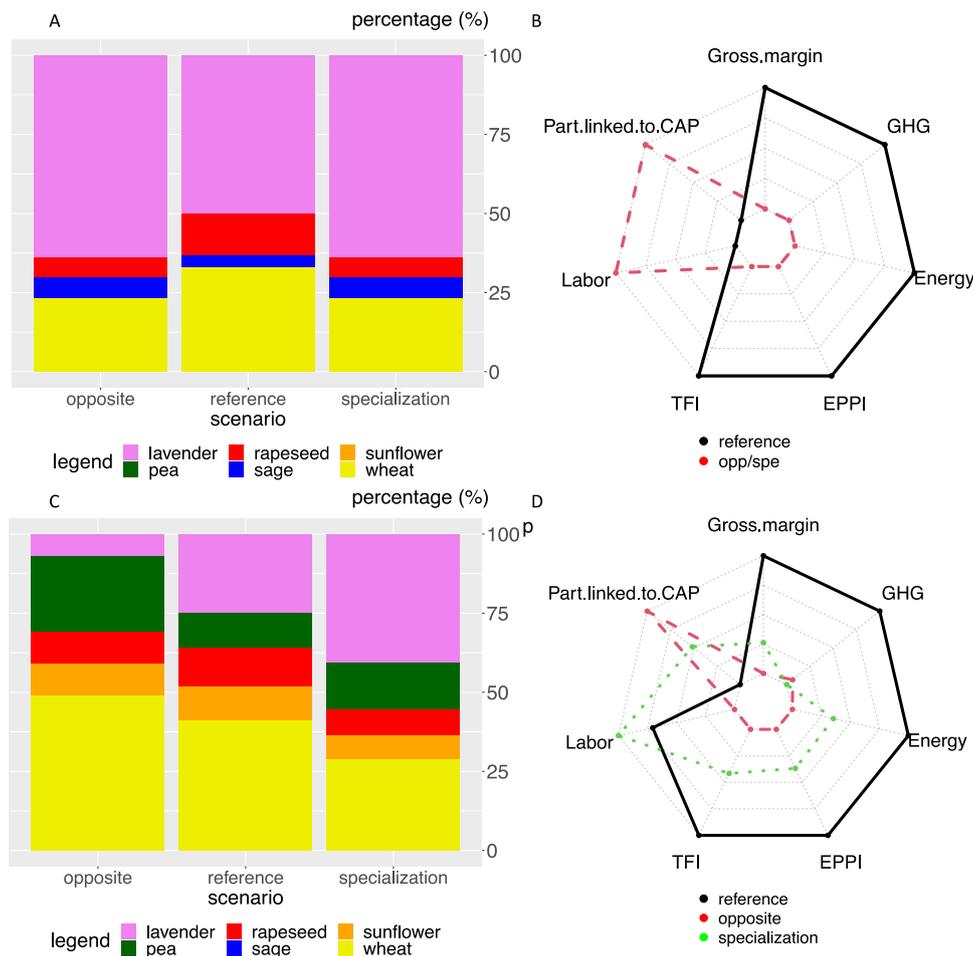


Fig. 7 Results of the simulations for the reference, “opposite strategies,” and “specialization” scenarios, in terms of (a, c) cultivated crops and (b, d) performances, for an average hectare of a typical specialized farm (a, b), and a typical non-specialized farm (c, d). Note that the adaptations are similar for the two scenarios of typical specialized farms, and that only non-irrigated farms are included. The gross margin is expressed in €/ha (min=630 and max=1015 in b; min=432.8 and max=784.7 in d); GHG corresponds to greenhouse gas emissions, in TeqCO_2/ha (min=1556 and max=1927 in b; min=1511 and max=1831 in d); energy to energy consumption,

in MJ/ha (min=14,150 and max=16,130 in b; min=12,155 and max=14,596 in d); EPPi to Environmental Phytosanitary Pressure Index, unitless (min=2 and max=3.5 in b; min=1.4 and max=2.5 in d); TFI to Treatment Frequency Index, unitless (min=2.7 and max=3.8 in b; min=2 and max=2.9 in d); labor is expressed, in hours/ha (min=8.7 and max=9.4 in b; min=5.7 and max=7.5 in d); and part linked to CAP is the share of CAP subsidies in the gross margin, as a percentage (min=27% and max=39% in b; min=36% and max=64% in d).

the two scenarios; we only considered non-irrigated farms (not to confuse effects). For these typical farms, there was a large increase in the area cropped with lavender, with only four crops in both scenarios (Fig. 7a). Consistent with the regional scale, all environmental indicators improved in the scenario when compared to the reference (lower GHG emissions, energy consumption EPPi and TFI, Fig. 7b). The gross margin in the scenario was 62% of the reference value for specialized farms for reasons similar to those at the regional scale, together with an increase of labor (and associated costs). As the gross margin decreased, the part of the CAP subsidies increased as compared to the reference situation (Fig. 7b). For non-specialized farms, the crop

shares changed inversely in the two scenarios; the area of durum wheat increased in the “opposite strategies” scenarios and decreased in the “specialization” scenario (Fig. 7c). By contrast, but logically, lavender crops increased in the “specialization” scenario and decreased in the “opposite” scenario. As for specialized typical farms, their environmental performances improved in the two scenarios, when compared to the reference (Fig. 7d). The gross margin also decreased along with an increase in the relative part of CAP subsidies, which was highest for the “opposite strategies” scenarios (Fig. 7d). The feeding performance decreased for both scenarios, with the region being able to feed in total 3886 persons per year in the specialization scenario (5460

persons per year in the opposite scenario), as compared to 6820 persons per year in the reference situation. It was due to the increase in lavender and sage areas, having no feeding value, in the specialization scenario, and to the decrease of rapeseed and increase of sage areas in the opposite scenario. The only performance for which the two scenarios did not show the same trend is the labor: it increased for the “specialization” scenario (for the same reasons mentioned before) and decreased in the “opposite strategies” scenario (replacement of lavender, requiring numerous working hours, replaced by other crops).

The decrease in gross margins, associated with revenue being more dependent on CAP in all situations (CAP subsidies are those of 2014–2020 for scenarios, and 2003–2013 for the reference situation), also led to vigorous discussions on the difficulties to be expected should the anticipated changes (climate, price of lavender oil, price of inputs) actually happen. It stimulated discussion on ways to reduce such vulnerabilities. However, while diversification is usually seen as a way to reduce vulnerability (Lin, 2011), actors wanted to explore a scenario in which all farms would get more specialized in lavender. While this might make sense in response to the simulated crisis (climate change, CAP reform, decrease in lavender price, and increase in input price), it focuses on a short-term response. This questions long-term performance, where resilience is usually favored by diversity (Abson et al. 2013).

The actors considered the collectively designed model to be coherent, although perfectible (TFI of some crops was considered too low), for simulating how changes in practices, such as more efficient technical management of irrigated crops, would impact performances. Thus, the model fulfilled its main objectives of quantitatively assessing scenarios with different criteria related to sustainability and acting as a “boundary object” for stimulating collective sharing and learning (Star, 2010). Although we did not formalize instances of acquired knowledge, they were highlighted by some actors during the study. There was a difference between recognized “source” actors with extensive knowledge on the local agricultural systems, and “well” actors, who used the opportunity to learn about the local network and agricultural system (these were mainly individuals new to the area, or involved in a specific topic, such as organic farming). However, even for “source” actors, some specificities (e.g., irrigation) were clarified during the process. A more in-depth study and reinforcement of the collective examination of the nature and relevance of possible adaptations might be pursued by developing a role-playing game based on the simulation model (as seen in Souchère et al. 2010).

Only two of the model’s indicators were related to the social aspect of sustainability: feeding performance, and labor. Aspects such as the contribution of agriculture to

employment (Reidsma et al. 2018), the quality of life of the farmer (access to social infrastructure and education for example) (Van Cauwenbergh et al. 2007), or the social and cultural acceptability of certain modifications in the agricultural system (Sattler et al. 2010) have been explored by other models, but they are difficult to quantify (Rossing et al. 2007).

Our approach led to a simulation closer to (data-intensive) IAAS tools than those of companion modeling (agent-based models), but it maintained a focus on providing a framework to support the reflection of actors at a territorial scale, rather than one directed solely at providing information for decision-making. Its shape and content were strongly influenced by the CM process, leading to an original, simplified and stylized spatial representation of the plateau, together with indicators representing the participants’ core issues. We believe that the spatial representation, although simplified, helped these participants share their perceptions of the plateau, and decreased the “black box” effect of usually complex, pre-defined, IAAS tools. The CM process led to multiple iterations, which helped to counteract the potentially important effects of the unstable participation during the process (ranging from 3 to 12 participants, Fig. 2). These iterations, at the core of the adaptive approach, were important for some model elements (e.g., exchanges and revisions in the spatial representation) but also for exploring adaptation strategies, which varied among farmers (“opposite strategies”) and other actors (“specialization”). In that sense, our approach helps to bridge the gap “between analytical-systemic and deliberative approaches” (Allain et al. 2020), which is seen as necessary in order to generate an informed dialogue between different agricultural system alternatives. However, the question remains regarding the fluctuating participation we observed, and the difficulty to mobilize farmers in the workshops. Although we found a way to engage farmers in another way, i.e., with individual interviews, this also questions their inclusion, and interest, in such exploratory process. One should also note the “decrease” in both the number of participants and the thematic diversity they represented, between the initial 24 interviews and the participation to the workshops. This could explain the strong focus of the model on the dominant cropping systems in professional farms, and the exclusion of small farms and activities marginal in the territory (no livestock, no beekeeping). This focus could be considered as a restrained vision of the agricultural systems linked to this participation bias, given the involved stakeholders affect the process outcomes (de Vente et al., 2016). While we tried to avoid this bias through the initial 24 interviews, it remains that actors’ involvement in such exploratory processes is a challenge. The loss of participants could be due to several causes, e.g., power asymmetry, inadequacy between the participatory process and the actors’ interests, lack of technical capability

(Reed et al., 2013), and support of a key local actor (Ericson, 2006). While it is difficult to analyze globally the reasons of participants leaving the process, some reasons were orally cited: “I did not see the objective at the last meeting, the process is too long and I won’t participate anymore” (one farmer); “There are too many uncertainties, making predictions is useless” (one farmer); “I have no time for this, but I am interested in the result” (one regional actor); “There are too many projects, and yours does not come from a local demand”. This diversity highlights, again, the difficulty for long-term actors’ involvement. While some of the previously formulated limits/criticisms could not be solved by the research team (e.g., local demand), we could have made choices to overcome some. First, we observed that the two actors supporting the project were not recognized enough locally to stimulate the participation. Second, we failed in mixing farmers with other actors in the workshops. A way could be to make separate meetings. Third, we may have partly failed in explaining the purpose of the process, which did not aim to predict the future, but to think on the possible futures, on the adaptations of the farming systems and their impacts on sustainability, and most of all on sharing experiences, knowledge, and perceptions. However, although fluctuating, some actors key to the territory participated to almost every workshop, and these actors acknowledged the outcomes of the process, even willing to pursue it.

4 Conclusion

In this study, we developed an innovative modeling approach aimed at promoting the sustainability of an agricultural system through sharing the perceptions and knowledge among actors. This approach, based on the co-construction and use of an evaluation model for the agricultural system, made it possible to explore the performances of that system under different scenarios. Despite the inherent technical requirements which can limit the solicitation of actors during the evaluation of agricultural systems, our approach enabled the co-construction of a multi-scale, multi-criteria, and prospective evaluation model of the agricultural system of the Valensole Plateau. The approach involved actors at all stages of the model construction. The articulation of the interests, points of view and knowledge of various actors, as well as the addition of sometimes uncertain and scarce data, is an innovation that was crucial to the success of this approach. This process stimulated collective reflection among the actors involved and created a learning experience with the sharing of perceptions and knowledge about the agricultural system. The co-constructed simulation model was considered relevant by all the participants, who expressed the desire to continue improving it, exploring new scenarios,

and discussing the results obtained with the farmers. This can be interpreted as a sign of ownership of the process and its results. Our method proposed, for the first time, a joint use of CM and IAAS. It could be adapted to other territories and issues, although we acknowledge that tool transfer remains an open question in such approaches.

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Availability of data and material Available on request from the corresponding author.

Code availability Available on request from the corresponding author.

Declarations

Ethics approval Not applicable.

Consent to participate All study participants gave informed consent to participate in the study.

Consent for publication CLP agreed to appear on the photograph presented in Fig. 1.

Conflict of interest The authors declare no competing interests.

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