How to intensify collaboration in a participatory modelling process to collectively design and evaluate new farming systems

Jean-Marc Barbier,[1,2] Caroline Tardivo,[1] Sylvestre Delmotte,[1] Roberto Cittadini,[3] Laure Hossard,[4] Christophe Le Page[5]

[1]INRAE Ringgold Standard Institution – ACT, Montpellier, France; [2]INRAE UMR Innovation 2 place Pierre Viala, Montpellier, France; [3]INTA Ringgold Standard Institution – EEA Balcarce, Buenos Aires, Buenos Aires, Argentina; [4]University of Montpellier, Ringgold Standard Institution – Innovation, Montpellier, France; [5]CIRAD Montpellier Campus International de Baillarguet Ringgold Standard Institution – UMR SENS, Montpellier, Occitanie, France

Highlights

- *A multi-disciplinary research team facilitated a process to help design and evaluate more sustainable agricultural systems with a group of stakeholders of a territory.*
- *To minimize bias, the selected study situation was new to all the scientists involved in the process.*
- *The collaboration led to the construction of a simple transparent model that helped exploring disruptive scenarios and stimulated lively debates on preferred futures.*
- *The model concentrated all the new knowledge produced and served as an intermediate object around which exchanges were organised.*
- *Despite the constant concern to collectively decide any implementation details and to share simulation results, maintaining the broadest possible participation over time remained problematic.*

Abstract

Agricultural research is expected to foster agro-ecological transitions. For that purpose, methodologies of participative integrated assessment of new farming and cropping systems are requested. However, the territory level and the stakeholders' participation are often not sufficiently embraced. Based on the companion modeling approach, a group of researchers from different disciplines experimented an approach where researchers and stakeholders collaborated intensively all along the process of design and use of the model. The researchers selected a small rural area where agriculture plays a major role (Valensole plateau, south of France) and where they had not carried out any investigation before. In such conditions, we argue that the interactions between researchers and stakeholders involved in the co-design from scratch of a simulation model stimulate a collective reflection about the sustainability of current and alternative farming systems. This article describes the different phases of the process from stakeholders' enrolment until the final discussion of the results provided by the model. It underlines the conditions that favored the emergence of consensus and the production of a new set of knowledge. It emphasizes how the discordances between data and disagreements between stakeholders were used to stimulate collective debates and underlines the role played by the model. Finally, the article discusses the drawbacks that the approach did not overcome.

Correspondence: Jean-Marc Barbier, INRAE – ACT, INRAE UMR Innovation 2 place Pierre Viala Montpellier 34000, France.
E-mail: jean-marc.barbier@inrae.fr

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Introduction

Challenging stakeholders' participation in agricultural research

Some streams of research pursue the objective to act in the real world to find and experiment possible solutions to specific problems. They also aim at producing knowledge about the studied situations, drawing lessons about the changes that have been undertaken and experienced (Hugon and Seibel, 1988; Liu, 1992; Albaladejo and Casabianca, 1997). In general, such streams of research encouraged the creation of so-called 'participatory' or 'collaborative' schemes (Greenwood, 1993; Gonzalez-Laporte, 2014). These strategies of research have been mobilised in various domains and especially in agriculture (Pretty, 1995; Eksvärd and Rydberg, 2010; Varela-Ortega, 2011), mainly when it came to imagine new forms of natural resource management and land use in rural areas.

Agriculture is experiencing major crises: land degradation, water shortage, climate change, loss of biodiversity, commodity price volatility. Because of this, the agricultural sector is the object of tensions and confrontations in front of which transformation options should be debated and prioritized. The vision of a necessary and peaceful coexistence of different models of agricultural development cannot hide the power struggles influencing decisions about regulations, support and credits (Gasselin *et al.*, 2020). Any intervention at the landscape level must therefore deal with participation to consider the diversity of visions, positions and strategies of the various actors. These actors can be individuals acting in their own name and/or on behalf of groups supporting various interests. Above all, agriculture consists of manipulating living organisms and managing natural processes; despite the technology, these processes are not totally predictable, they are subject to hazards and this leads to strong uncertainties as to the effects of the changes in practices that the stakeholders could envisage.

Agricultural science has long been concerned with taking the views and needs of stakeholders (mainly farmers) into account to increase the chances of success of agricultural development projects (Chambers *et al.,* 1989; Mettrick, 1993). Progressively, from the mere purpose to describe and understand to better guide research and action in the field, researchers moved towards taking greater account of the capacity of farmers to judge and evaluate new technologies, to propose alternatives, and more recently to co-design such options with farmers. New concepts and methodologies have emerged: participatory design (*e.g.*, Jeuffroy *et al.*, 2022), multi-criteria evaluation (*e.g.*, Sadok *et al.*, 2009), companion modelling (Etienne, 2011), innovation tracking (Salembier *et al.*, 2016), *etc*. Today, at a time of agro-ecological transition, which requires designing systems adapted to a wide variety of situations, no one disputes the need to invent innovative systems based on the expertise, knowledge and know-how of all the stakeholders in a given territory.

A diversity of approaches and methods that do not give the same consideration to the views and needs of stakeholders

Various approaches and tools have recently been proposed by agricultural research to stimulate participation and dialogue between stakeholders in the agricultural sector to facilitate, through the use of models, the collective exploration of new, economically profitable and environmentally-friendly production systems. The literature provides classifications of these approaches (Voinov and Bousquet, 2010; Voinov *et al.*, 2016), identifies their key features (Neef and Neubert, 2011), or compares their characteristics (Berthet *et al.*, 2016; Delmotte *et al.*, 2013). In this paper, attention will be focused on Integrated Assessment of Agricultural Systems (IAAS) (van Ittersum *et al.*, 2008) and Companion Modelling (ComMod) (Bousquet *et al.*, 1999). These methods offer precise descriptions of the principles and actions to carry out when such research objectives are pursued. In addition, other authors suggest different kinds of models or tools to explore and assess possible futures for agriculture: spatial agent-based models (Filatova *et al.*, 2013), land use/land cover change models based on statistical analysis (Veldkamp *et al.*, 1996; Verburg *et al.*, 2004), and more recently serious games (Michel & Mc Namara, 2014; Martel *et al.*, 2022). In all cases, modelling is at the heart of the process. The model is primarily meant to assess different scenarios (Jakku and Thornburn, 2010). A scenario being composed of: i) a representation of the current situation (also called baseline scenario); ii) an identification of the drivers of change; iii) a description of the studied system transformations (Alcamo and Henrichs, 2008). Additionally, the model is also often considered as an intermediate or boundary object (Vinck, 2009) whose discussion underpins social learning (Star, 2010).

In this paper, we present and discuss a case study based on the joint use of the two first methodological frameworks mentioned above: i) IAAS; ii) companion modelling. First, IAAS allows for quantitative multi-criteria and multi-scale evaluations (Lopez-Ridaura *et al.*, 2002). It considers a detailed representation of the production systems *i.e.*, cropping systems, field and livestock management practices, which is necessary to reflect on technical alternatives for the sustainable management of agricultural landscapes. However, in IAAS, participation is mainly seen as a way of harnessing the knowledge (and data) of stakeholders. Very often, researchers use pre-existing mechanistic models which are not transparent to participants (Korfmacher, 2001). These models are complex, data-intensive, and often lead researchers to work with a pre-existing network of partners, knowledge and data (van Ittersum *et al.*, 2008; van Paassen *et al.*, 2007). As a result, the diagnostic, engagement and involvement phases of the participating actors are very rarely problematic and optimization tools are used in order to find out the "best solutions". Furthermore, IASS approaches are poorly spatially explicit, *i.e.*, they hardly consider the interactions between spatial attributes and agent's preferences. Second, companion modelling is defined as an approach that facilitates the collective decision-making process in the case of complex and uncertain situations. It offers a framework for the clarification of points of views and criteria used and referred to by the different stakeholders. What is sought is no longer the quality of the decision (there is no best decision), but rather the quality of the process that leads to one decision (Commod, 2009). This approach places greater emphasis on the "co-construction" of models and the learning that takes place during the process within the group of actors. In this case, simplified models can be used, which are based more on the participants' knowledge than on a large set of data (Le Page & Perrotton, 2017). The companion modelling approach opted for the multi-agent system modelling paradigm. In such type of models, the interactions between decision-making entities (*e.g.*, actors in the agricultural system) can be considered. Furthermore, their content is easily understood by stakeholders (Le Page *et al.*, 2012; Delmotte *et al.*, 2013), in contrast to optimisation models or dynamic equation-based models involving a higher level of abstraction (*e.g.*, Hossard *et al.*, 2013). Moreover, companion modelling does not use agent-based models as optimization tools to detect the best solutions but rather as exploration tools to foster collective discussions on interesting alternative options. When dealing with agricultural systems, companion modelling studies generally focused on the collective management of shared resources, for example soils and their fertility (Souchère *et al.*, 2010), irrigation water (Daniell *et al.*, 2011), or land tenure (d'Aquino & Bah, 2013).

Design and implementation of a hybrid, highly collaborative approach in a new case study

We decided to combine the best characteristics of the two approaches previously mentioned in a collaborative work with stakeholders aimed at designing and evaluating scenarios for agricultural changes on a landscape level. We looked for stimulating mutual learning (between stakeholders and between researchers and stakeholders) and encouraged the transformation of representations and knowledge, to envisage new actions to be implemented in the territory. The research team (six persons in total) was composed of an equal number of members with backgrounds in IASS and companion modelling, composing a multidisciplinary group of researchers (agronomists, sociologists, modellers). As this team had already experienced working situations where their legitimacy towards stakeholders was firmly acquired, it was decided to test the combined approach in a new place; thus the team had to acquire legitimacy, to collect new sets of data and knowledge, and to build a dedicated model.

The chosen place was a 50,000 ha rural area in the south-east of France (Valensole plateau), where agriculture covers half of the territory (Figure 1). The soils are mostly superficial and stony. The Mediterranean climate causes periods of water shortage for crops and this problem is worsened because of climate change. Irrigation is possible in a small part of the territory, but it is not largely used by farmers because of excessive costs. The farms are generally large (100 hectares on average) and based on durum wheat and lavandin, a semi-perennial (5 to 15 years) perfume plant. These two main crops cover more than half of the agricultural area. A pest causing the decline of lavandin, which is the main cash crop, is currently expanding; in terms of durum wheat, its yields vary greatly due to intensifying droughts. To cope with these threats, two strategies are being discussed: crop diversification (forage crops, legumes, or perennial crops) and extension of the irrigation network. In such a context, the research team became involved over a two-year period by organizing a series of workshops.

While detailed information on the model itself and the main results obtained through its use are described in Hossard *et al.* (2022), our objective here is to highlight some of the necessary conditions of success when bringing together different stakeholders with the aim of co- producing new insights for local agricultural development. In the paper we first describe the collaborative approach, and we highlight the way we manage and monitor it. In a second section, we show how we build the model and the scenarios. We illustrate, through examples, how this process has nurtured an interactive dynamics of knowledge co-construction and the type of outcomes it has produced. Finally, we draw some lessons on the capacity of this original approach to foster more effective adaptations of agricultural production systems.

Methodological principles of the participatory approach

Participatory modelling applied to agricultural studies often defines, *a priori*, an "ideal" sequence of stages (Delmotte *et al.*, 2016; 2017): i) regional agricultural characterization; ii) enrolment of stakeholders; iii) conceptual model design and simulation model implementation; iv) co-construction of scenarios; v) identification of criteria and indicators for their evaluation; vi) processing, data analysis and result formalization; vii) discussion of results. However, this overall organization does not pinpoint how to foster and control stakeholders' participation throughout the process.

The launch of the participatory process: the implementation of the first stages

During the two-year study period, a total of eight collective workshops (of a duration varying between half a day and a complete day) were organized. Each workshop had a specific topic, and participation varied between workshops (Figure 2). Figure 2 shows that the engagement of a steady number of stakeholders became concrete progressively and significantly materialized at the beginning of the third workshop (W3).

To define the agricultural issues to be addressed, the actors to be involved and the system to be represented, 24 representatives of institutions (cooperatives, associations of producers, technical

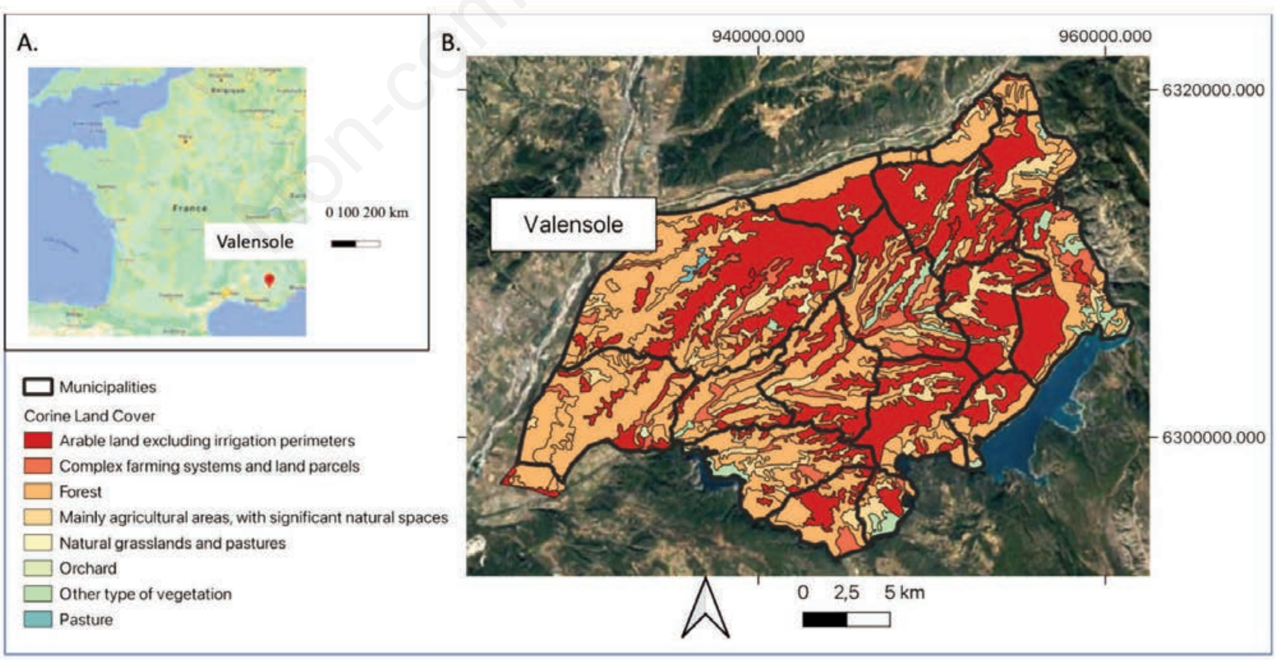

Figure 1. Location of the Valensole Plateau in Southern France (**A**) and its main land uses (**B**). The city of Valensole is located in both maps. In B), land uses are based on Corine Land Cover classes (2012; https://www.data.gouv.fr/fr/datasets/corine-land-cover-occupation-des-sols-en-france/), gathering some land uses (*e.g.*, forests); the base map is from Landsat 7 (2006).

institutes, chambers of agriculture, irrigation companies, natural regional park) were interviewed individually. They were questioned about: i) their missions and/or actions on the Valensole plateau; ii) their perceptions of the agricultural issues; iii) their awareness of the most influent stakeholders; iv) their visions of the future of agriculture in this area; iv) their expectations about the foreseen collaborative work with researchers. The contents of these interviews were formalised in cognitive maps (Eden, 2004; Tardivo *et al.*, 2014) that identify the objects, the actors linked to these objects and their interrelationships.

At the same time, an agronomic diagnosis (according to the method of Doré *et al.*, 1997) was conducted with 32 farmers. The results of this diagnosis were communicated to the stakeholders (W1, Figure 2), which allowed progress in identifying the agricultural problems and issues in the area.

At the end of this first step, all of the 24 actors surveyed were invited to a second workshop, where half of them (12) were present (W2, Figure 2). The purpose of this workshop was: i) to precisely delimit the study area; ii) to decide on the priority issues to be addressed; iii) to define the production systems to be studied; iv) to draw a first conceptual model.

Assuming roles and getting involved in the production of data

The research team interacted with stakeholders, most often institutional stakeholders from agricultural and environmental sectors, named “participants”. By stakeholders we mean here both farmers and advisory and extension organisations/institutions. Together, the researchers and stakeholders formed a permanent working group, which met regularly in workshops over a period of two years. While the researchers proposed and organised the smooth running of the whole process, they also played a facilitating role in helping the participants to express themselves and work in a collaborative manner (Scholz *et al.*, 2013). The proposals, deliberations and decisions regarding the choices to be made to build and parameterise the model and write the scenarios to be explored were made by the working group. All participants were local experts specialised in a sector (lavender, wheat) or a field of activity (*e.g.*, biodiversity), or with an overview of the territory. Some of them (*e.g.*, managers of technical institutes) were also mobilised individually to provide knowledge and data for the model. After unsuccessful attempts, it was decided to mobilise farmers individually as a second phase, to validate, criticise or correct the choices and representations made by the working group

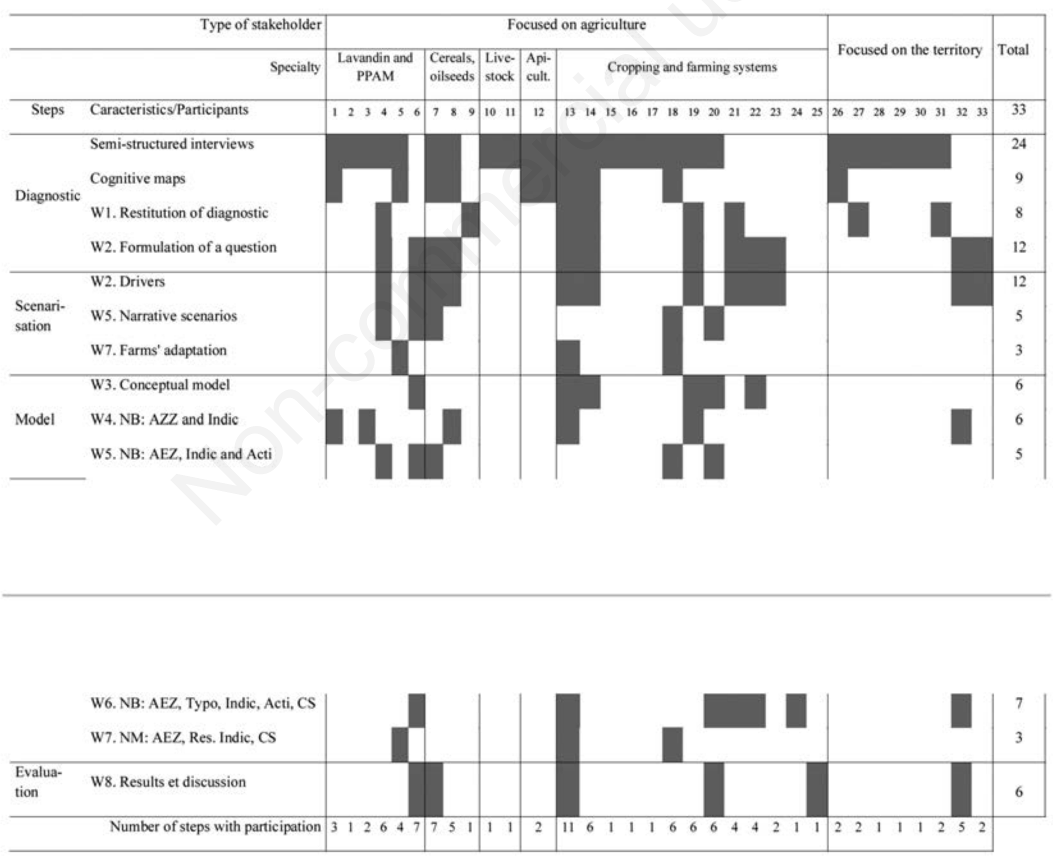

Figure 2. Stakeholder participation. Each column corresponds to a participant and each row corresponds to a workshop. The last column shows the number of participants per workshop; the last row shows the number of workshops attended per participant. PPAM, perfume and medicinal plants; Api−cult, apiculture; WX, workshop n°X; NM, numeric model; AEZ, agroecological zoning; Indic, indicators choices and calculation method; Acti, definition of farming activities; Typo, farm typology; CS, cropping systems of farm types; Res. Indic, discussion on the first results obtained (indicators values). Cropping and farming systems’ participants correspond to people having a cross−functional approach to several types of cropping systems (*e.g.*, advisors from Chamber of Agriculture).

and provide additional data. To characterize the agricultural context, the approach mobilised secondary statistical data proposed and provided by both the stakeholders and the researchers. The data were extracted from: i) farmers' Common Agricultural Policy (CAP) declarations; ii) a cropping system survey (Supagro, 2013); iii) a territorial (farming) survey (Lang & Ramseyer, 2011). Participants were constantly invited i) to share their knowledge and representations of current phenomena and dynamics; ii) to communicate data or data sources; iii) to criticize the results of laboratory treatments; iv) to build and validate, from a multi-agent system perspective (see below), the choices of structure and parameterisation of the model.

A flexible and adaptive process that needs to be monitored

A monitoring strategy had to be set to adjust and refine the choice of methods and tools for the specific needs that would becoming apparent along the participatory process. In this study, all the steps were taken from a blank sheet of paper (*e.g.*, no data existed), with the notable exception of the regional agricultural diagnosis (Lang & Ramseyer, 2011).

In a participatory process, the approach, its course, and the structure of the model, must be able to adapt to changes in the partnership context (new arrivals, withdrawal of certain participants) and to the dynamics created by the deliberative process (preferences, choices and proposals made by the participants). This flexibility, advocated by all specialists in participatory modelling approaches (Voinov & Bousquet, 2010), requires *in itinere* assessments to properly monitor and analyse the progress of the collaborative process. With that objective, we considered methodological frameworks that enable organising reflective analysis within research teams (Van Mierlo *et al.*, 2010; Neef & Neubert, 2011; Gouttenoire *et al.*, 2014; Hassenforder *et al.*, 2016). This led the research team to self-evaluate: when achievements deviated from expectations, the process could then be corrected or redirected. To inform the different themes and criteria of a reflective analysis grid, field data and observations were captured. The materials used as a basis for the monitoring and evaluation of our approach came from five main sources: i) a logbook, which describes on a weekly basis the progress of the process, relational events with the actors, personal impressions, and any element that may influence the process; ii) a questionnaire submitted after key workshops to the participants, in writing or by telephone, aimed at collecting their opinions and feelings on the progress of the process and the intermediate results obtained; iii) verbatim records: during each workshop, verbal exchanges were recorded, and transcribed back in the office. In addition, researchers who were not facilitators observed the behaviour of the participants and their interactions iv) debriefings: each workshop was followed by an 'on-the-spot' debriefing meeting between members of the research team; v) reflective analysis sessions: bringing together all the researchers involved, it aims to put each stage into collective perspective as it came to an end. Revisiting and re-analysing the events, several months after their occurrence, allowed researchers a step back towards an ex-post re-interpretation.

Participatory process outcomes: conceptual and simulation models and scenarios to be assessed

Delineation of the studied system and issues to be addressed

The conceptual model (Figure 3) was co-designed through a selection of key concepts made by the participants from the constitutive components of the cognitive maps provided by the research team. The participants decided to focus on the farms based on lavender and durum wheat. At the end of this first stage of the work, we could predict that the interest for our investigation was going to be shared by four groups of actors: the irrigation company, the extension services dedicated to agricultural support (for cereals and for aromatic plants), the regional natural park in charge of reconciling nature and agriculture, and the association of organic producers. The following steps of the work confirmed this first impression (Figure 2), but as far as the process move forward we were able to better understand the real motivations of these stakeholders. It was expected that our results would: i) draw new insights for the extension of the irrigation system; ii) bring new ideas to cope with the actual issues in case the extension of the irrigation network would not be effective.

Choosing and validating a computer simulation model

To match the objectives of the researchers (integrated assessment of scenarios) and expectations of the stakeholders (territorial evaluation of changes in the production systems), the research team decided to develop an agent-based model that provided a set of farming features and an easy-to-grasp representation of the agrarian structure of the Valensole plateau. The model had to be easily understandable and simple to modify to consider stakeholders' propositions. This model was run to compute performance values (according to the selected criteria indicated by stakeholders) of different co-designed scenarios (for instance: extension vs no extension of the irrigation system). The exploration of a given scenario triggered discussions about new systems to be designed by the participating stakeholders.

The validation of the model, implemented using the Cormas multi-agent platform (Bousquet *et al.*, 1998), is a validation by both use (the participants acknowledge the use of the model and its effectiveness), and facts (the results obtained with the current data fits with the present time). The first guarantee of validity is gained by means of the co-construction process. The research team did not arrive with a pre-existing model, but only with a general framework with the potential to effectively represent the Valensole plateau agricultural territory. All along the participatory process, from workshop W3 to W7 (Figure 2), stakeholders and researchers decided what objects to represent, what relationships exist between them, what set of data to explore, *etc*. The model is then the result of a collective agreement. The second guarantee is obtained by presenting to the participants the results obtained by running the model under a "business-as-usual" scenario (corresponding to the current situation). The model is then declared satisfactory by comparing the model's outputs: i) with official statistical data (*e.g.*, regional crop rotation from CAP declarations); ii) with the participants' or other experts' knowledge. A third type of validation occurs at the end of the process when the results of the alternative scenarios are presented. However, this cannot be strictly considered as a validation as it concerns situations that do not exist at the present time. What arises at that moment are opinions of the stakeholders about the possible consequences of plausible futures; it creates discussions and some results may be received with perplexity. In this case the model can be questioned and has to be checked again. However, more often what emerges at this time are new ideas of scenarios, leading to a new cycle of simulations, which may require further modification of the model.

Co-designing the computer simulation model

The co-construction of the simulation model required: i) to define the mode of representation of production conditions in the study area (mainly soils, spatially distributed within agro-ecological zones); ii) to describe the types of farms and their distribution; iii) to specify the crops management techniques and their associated performances; iv) to build scenarios of agricultural development; v) to choose evaluation criteria at the plot, farm, agro-ecological zone level and for the whole studied area; vi) to validate the model and eventually refine it; vii) to report and discuss the results obtained by running the model.

We detail thereafter three examples to illustrate how the reflections were organized during the collaborative modelling process in a permanent back-and-forth between laboratory work and participatory workshops, leading via compromises to the creation of various intermediate objects (maps, typologies, list of factors of change, *etc*.). The first example shows how the participating stakeholders helped the researchers to properly set the balance between a distorting simplicity and an unnecessary complexity regarding the agro-ecological representation of the territory. The second example shows how the categorization carried by the stakeholders resulted in dismissal of a certain number of farms due to a status judged as "unprofessional". The last example justifies the need to integrate the farmers' vision to concretely specify the adaptation of cropping systems to the changes defined in the scenarios.

Specification of the agro-ecological zones

Figure 4A shows the initial zoning proposed by the research team, with only two zones corresponding to low and high intensities of lavandin decline, and Figure 4B the final representation, agreed after several workshops (Figure 2). The incorporation of an intermediate lavandin decline zone was considered necessary by the participants to account for a progressive spatial phenomenon. A second adjustment was made so that the irrigable land corresponded to an area with low decline of lavandin. The participants characterised the soils by their depth, stoniness and organic matter content. They proposed the available water storage capacity (AWSC) a synthetic criterion with a strong impact on yields. However, it proved difficult to agree on the boundaries of the areas defined by the AWSC, due to the high heterogeneity of the soils (both intra and interplot). It was therefore decided to mobilise a 1:100,000 map of the AWSC of the Valensole plateau provided by a participant in charge of irrigation issues. A new zoning was then proposed by the research team. It was based on a South-West/North-East gradient. Each delimited "soil types zone" in Figure 4 represents a certain proportion of soils with high, medium or low AWSC. Heterogeneity within agroecological areas was thus introduced, while reflecting a gradient at the scale of the plateau. This principle was decided collectively by the researchers and the participants; the latter reduced the number of AWSC classes to three (instead of the initial five), allowing diversity to be considered without making the model excessively complex. The exercise led to the delimitation of seven agro-ecological zones (Figure 4).

The specification of 'typical' farms

A typology of farms was developed on the basis of three criteria: size, degree of specialisation in lavandin, and ability to irrigate crops (accessibility to water and irrigation equipment). For these three criteria, the differentiation thresholds were determined by going back and forth between collective workshops and data anal-

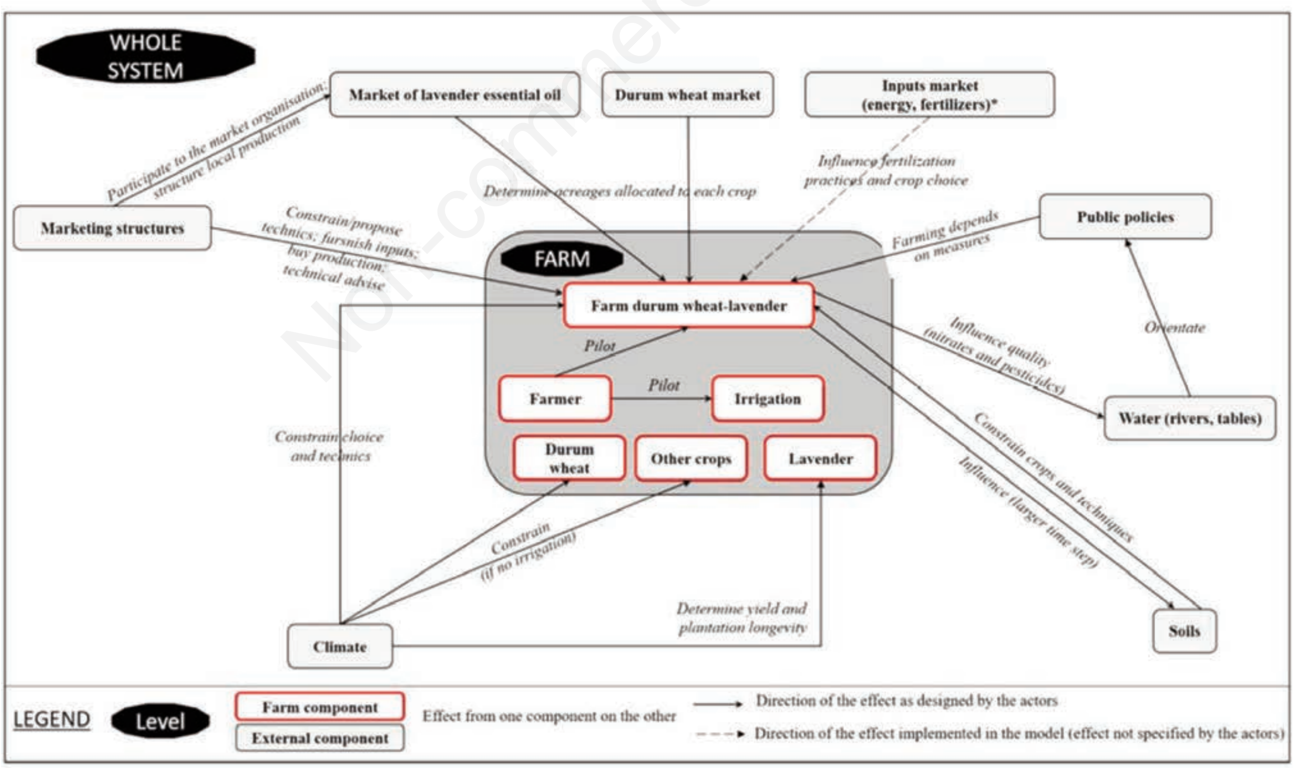

Figure 3. Conceptual model of the agricultural system of farms mainly cropping durum wheat and lavender (adapted from Hossard *et al*., 2022). For instance, marketing structure will participate to the organization of the market of lavender essential oil, and structure the local production of the Plateau de Valensole. *The inputs market was added at the end of the workshop; its relationship with the other components was not discussed with stakeholders so only its representation in the model is indicated here (hatched arrow).

ysis (CAP declarations). Regarding farm size, it was decided that farms of less than 30 ha or cultivating less than 5 ha of lavandin were too small to be considered as professional farms, so it was useless to represent them in the model. The most important point, according to the participants, was to distinguish between medium-sized farms with high equipment depreciation costs per hectare and large farms with less labour per unit area, this distinction being related to their flexibility to adapt to changes. Examination of the variability of farm sizes (CAP data) led us to set a threshold of 100 ha (equal to the sample average), which allowed us to distinguish two types of farms: medium (60 ha) and large (160 ha).

According to the participants, the level of specialisation in lavandin influences the way the farm's turnover is constituted, and conditions the farmers' strategic choices. Indeed, lavandin is an important source of income but requires a lot of labour (distillation and planting). Farms specialised in lavandin would thus simplify the way they grow the other crops and would diversify their crop rotation less. It was agreed to define the specialisation in lavandin on the basis of its relative surface cultivated with lavandin. The median (35%), calculated from the CAP data, was chosen as a threshold: farms with more than 35% are considered as specialised. Irrigated farms are the ones located in the area where water is available and that own equipment to irrigate.

Scenario building

In the case of the Valensole plateau, the scenarios have been designed by the stakeholders following a method suggested by the research team. During the second workshop (W2 in Figure 2), the drivers of future agricultural change in the study area were settled; four of them were considered as critical: i) the intensity of lavandin decline; ii) the expansion of the irrigation network; iii) the increase in the occurrence of extreme climatic events; iv) the evolution of prices of the agricultural inputs and products. The participants then wished to describe a "pessimistic" scenario that combined greater decline, non-extension of the irrigation network, increased spring droughts and lower prices for lavandin essential oil. However, they declared themselves not qualified to imagine the adaptation strategies of the different types of farmers who would face such conditions. Five farmers, who did not participate in the workshops, were then asked to contribute. They considered this scenario as plausible and confirmed that it corresponded to their concerns. Two contrasting adaptation strategies were then imagined by the farmers: i) the increase in the area planted with lavandin. In a general context of decreasing yields of all crops due to droughts, lavandin would remain more profitable than other crops, therefore increasing the area planted with lavandin would allow the farms to maintain their income; ii) crop diversification. For some participating farmers (3 out of 5), the solution would be to reduce the area planted with lavandin in favour of other crops (rape, sunflower, peas). According to these farmers, reducing dependency on lavandin cultivation would reduce the growing risks linked to rising decline, droughts and falling prices.

The first strategy was defended by large farms specialised in lavandin. The second strategy was supported by smaller farms that made fewer investments in lavandin and were already partly diversified. When these two adaptation strategies were presented to the institutional participants (Workshop W7, Figure 2), the second one was hardly discussed because considered as unrealistic by some stakeholders. It was then decided to evaluate two separate scenarios for farms not specialised in lavandin: a 'farmer' scenario (decrease in lavandin area and diversification), and a 'manager' scenario (increase in lavandin area).

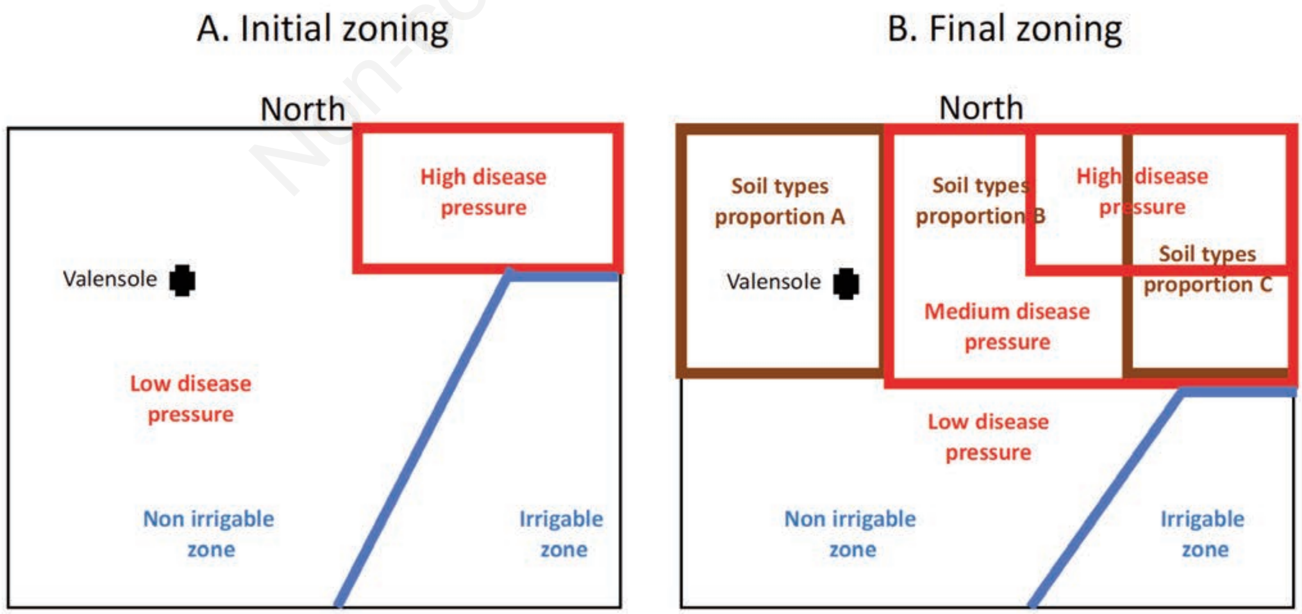

Figure 4. Representation of initial (**A**) and final (**B**) agro−ecological zones. Disease pressure relates to lavandin decline, a disease-causing plant death.

Discussion

Dynamics of stakeholder participation: self-exclusion, stabilization and complementarities

The monitoring of the participatory process allowed us to explain the evolution in terms of the number of participants at the successive workshops (Figure 2). Half of the stakeholders invited to the second workshop (W2, Figure 2) did not wish to participate further because they considered their activity not sufficiently territorialized or too "secondary" in the studied territory (*e.g.*, breeding and beekeeping), or because they belonged to institutions whose activities were not limited to the Valensole plateau and/or to agricultural issues. At the start of the model co-design (from workshop W3), participation was again restricted (seven persons during workshop W6, three persons only during workshop W7, for example). This second disaffection can be attributed to the collective decision made by the end of workshop W2 to work only on farms growing field crops and lavandin. Several authors (Barouch, 1989; Sébastien & Brodhag, 2004) argued that, when negotiation is at stakes, a participatory process must pay attention to the non-participating actors; they may have been forgotten, absent or comparatively weak (poor in resources). In our case, our analyses show that the actors who decided not to participate considered that they were not concerned by the delineation of the study to the same extent as those who participated. However, from W3, there was a relative stabilisation of the institutional representatives, with five keen participants: the Chamber of Agriculture, the Verdon Natural Regional Park, the perfume plant sector, an organic farming association (agribio04) and the local cereal cooperative. The first modelling workshop (W3) had strongly clarified the second phase of the work that was then starting; consequently, each of these institutions decided to delegate the most available, competent and/or concerned person. As recently stressed by Worosz (2022), it is critical that some individual participants behave as "boundary players" with multi-dimensional skills who transcend the science, facilitate cooperation, and reduce transaction costs. They are invaluable allies for building the trust-based relationships that are fundamental to the approach, satisfying organization expectations, and managing the costs of participation throughout the entire process.

The separation between institutional actors and farmers was decided on the fly because the inclusion of the latter in the collective workshops had not been satisfactory (asymmetric speaking, difficulties in expressing a regional point of view). This difficulty has been emphasized by other authors (Michel *et al.*, 2018), who point out that very often, the offer of participation doesn't make farmers at ease in the arena of discussion and does not correspond to their habits in terms of the representation of their opinions. Consequently, the research team opted for a strategy of mobilising farmers individually in between collective workshops. It is worth noting that the institutional participants declared themselves to be bearers of partial knowledge and acknowledged the importance of considering the points of view and knowledge of individual farmers.

Stakeholders and the diversity of learning

Based on the surveys conducted at the end of the project, we observed that the intensity of learning varied according to the participants. Initially, we identified a group, which we described as "resource participants". They have often worked for a long time in the studied area, have in-depth knowledge of the agricultural systems, have a large social network within the territory and, because of their socio-professional position, are in possession of strategic information that enables them to influence certain decisions. The participation of the members of this group is not regular: while they genuinely contribute to the process by providing some of their knowledge, they will strongly give their opinion on the possible orientations of the work, which explains a strong participation at the beginning of the process that becomes more sporadic later on. On the other hand, the participants who can be described as "sinks" are often people who have only recently started working in the region or who want to connect with others. Participating in the process allows them to strengthen or even build relationships with other local stakeholders. These participants declare that they have learned a lot about the different visions of development for this region. More than the results (from the model outputs), what appeared important to them were the discussions they generated, the possibility of better identifying the interests of each person and learning about "how to create a collective dynamic". Schmidt *et al.* (2020) identified 4 differentiated objectives for stakeholder involvement in transdisciplinary research: i) the normative; ii) the substantive; iii) the social-learning; iv) the implementation objective. Our study shows that it is possible to embrace several objectives during the same process, each of the participants making their own arrangements along the way. We consider that the first group of stakeholders mentioned above were mainly motivated by participating to exchange and integrate various bodies of knowledge and perspectives to co-produce a socially robust and holistic understanding of the sustainability of agricultural systems in the Valensole plateau (substantive objective), whereas the other stakeholders were rather interested in improved mutual understanding of different interests, potential conflicts, values and capacities to establish new networks and to identify balanced solutions (social learning objective).

Degree of complexity of the model, transparency and respect for collective choices

The *ex nihilo* design of a computer simulation model, which was achieved progressively by means of choices agreed between participating stakeholders and researchers and supported by the processing of secondary data known to all, was not called into question. The initial option of a highly simplified and stylised representation (Figure 4) was never questioned or denigrated (it could have been described as simplistic). It allowed stakeholders to be directly confronted with the computer simulation model on three concomitant levels: i) by assessing its assumptions; ii) interpreting simulation results; iii) suggesting scenarios. Nevertheless, as highlighted by Becu *et al*. (2008), a very important task which falls to the research team opting for this kind of modelling approach consists of regularly reminding participants about the status of the simulation model as a tool to foster discussion about reality, and not as a reproduction of the reality. In the end, the model was considered sufficiently relevant, while remaining understandable.

Finding the right level of complexity for a simulation model is not an easy task, as the choice must ultimately be guided by the objective assigned to the model (Sun *et al.*, 2016). When this objective is unambiguously shared by all participants, the risks of rejecting the approach are minimised. Moreover, few discrepancies were encountered within the group of participants, and the values of the indicators for the current situation appeared to be consistent with reality. This cannot be disconnected from the precautions taken by the research team: i) to not sacrifice the initial phase of formulating the problematic to obtain relatively stable agreements by eliminating possible sources of conflict; ii) to clarify the principle of co-construction, to constantly re-explain the approach and the posture of the researchers and to precisely present the work carried out in the laboratory (data processing); iii) to always respect the agreements reached at the end of the collective workshops.

Interest raising and legitimisation

The initial phase of interest raising and enrolment of actors is not the one particularly well detailed and discussed in publications on participatory approaches (d'Aquino & Bah, 2013; Delmotte *et al.*, 2017). In this process of moving from the individual to the collective, we used a method to systematise the examination of the raw data from the individual interviews and to try to 'objectify' the analysis. To report the information obtained during individual interviews into forms that could be rendered during collective workshops, the "cognitive map" tool was used. This tool enabled the "filiation" between what was contributed by the people surveyed individually and what was returned to the group, leading those elements to be both transparent (the method is presented) and obvious (the person finds his or her contributions). Ginger (2014) highlights two dimensions of legitimacy in participatory modelling processes: procedural and scientific expertise. In our case, the legitimacy of the researchers was not built on the contribution of knowledge related to a particular technical field or regional knowledge of agricultural systems, but on their command of the process, on proposals for methods likely to lead to shared knowledge, and on their modelling skills. Clearly, we focused on the procedural dimension. The initial agronomic diagnosis and the surveys of institutional stakeholders did allow the researchers to enter the 'arena' without being totally devoid of a point of view, which made it possible, without imposing anything, to contribute to the debate.

Exchanges of knowledge and points of view: how to move from principled stances and corporate interests

The collective workshops have always led to a consensus between the participants as long as the topic of discussions dealt with framing the main question, delimiting the system to be studied, modelling it as a simplified representation and designing a simulation tool. Dissension emerged regarding the solutions to be found for the issues carrying an important stake. It is the farmer surveys that revealed discrepancies between the representations and future prospects of the institutional participants and the farmers' practices and visions. We have seen that a first divergence appeared on the strategies of adaptation to the proposed scenario: for the institutional participants, all the farmers (whatever the size of their farm) had an economic interest in increasing the area under lavandin, whereas some farmers tend to suggest a preference to go towards more diversification of crops. The simulation outputs appeared to be reasonably accurate considering the estimates of economic performances suggested by the participants. However, the multi-criteria evaluation revealed lower environmental performance (more plant protection treatments and more greenhouse gas emissions; see Hossard *et al*. (2022) for more details). Thus, this controversy has brought the debate into a more open field of sustainability and questioned more than just economic rationality, challenging the 'mainstream' model, and advocating that inclusive development also includes both ecological and social wellbeing (Pouw & Gupta, 2017).

A second divergence emerged about irrigation. Surveys of farmers revealed that they made few changes to their crop management techniques when the crop was irrigated, and did not necessarily obtain a higher gross margin, as the yield gains were cancelled out by the costs associated with irrigation. These results, supported by simulation outputs, were contested by institutional stakeholders. This called into question the project to expand the irrigation network, supported by at least one of the participants. Leaving aside their principled positions, the participants recognised that, even if there are irrigation professionals, the majority of farmers do not adapt their crop management when irrigating. While this is a major question mark over the appropriateness of financing the expansion of the irrigation network, all participants agreed that such an expansion should be accompanied by training and coaching of farmers. It was also agreed that it would be useful and interesting to carry out new simulations by developing an irrigation scenario based on adapted cropping techniques.

Conclusions

In this article we described how we conducted the collection, analysis, interpretation and valorization of agricultural knowledge and data and how we co-produced, in a process marked by a series of participatory workshop and different intermediate objects (*e.g.*, conceptual model, spatial representations, farm typologies, computer simulation model). For certain stages of the process, we indicated how the data was processed to allow the transition from one stage of the work to the next (*e.g.*, cognitive maps to make a transition between individual interviews and the first collective workshop). We illustrated, in three examples, how common representations deemed relevant and sufficient for the purposes of the work were constructed, thanks to the feedbacks between laboratory work and collective discussions/validations. It was the articulation between the empirical knowledge of the participants and the examination of statistical and survey data that made possible such reasoned and ultimately consensual choices. For the researchers, this articulation makes it possible to reduce the uncertainties linked to each of the two sources of information (Reed, 2008). For the stakeholders, a more scientific endorsement of their views and opinions was regularly requested. There was both extraction of knowledge and production of new knowledge.

The companion modelling methodological framework has proven to be relevant for developing a model that provides transparency and allows, despite its relative simplicity, quantitative assessments to be made on a wide range of criteria. It is the diversity of these criteria (agronomic, economic but also environmental) that allowed the evaluation to be placed in a sustainability analysis perspective. The agronomic and economic results of the computer simulations are primarily local in scope; these results should be supplemented by other simulations (the final workshop raised new questions). The model was not designed as a "disposable" model, whose usefulness lasts only as long as the project. The model's main function, as shown here, is to make people react, to shake up the obvious, taboos, received ideas or false consensual ideas. In moments of disagreement between actors concerning the solutions to be applied, the results of the model's simulations do not play the role of a judge, but rather of the emergence of more open questioning and the highlighting of sensitive or unspoken points.

The contribution of this case study is mainly methodological, setting out some reference points as to the way to engage various types of stakeholders in a social learning process towards sustainable agriculture. In particular, we showed that: i) the lack of data, knowledge and a priori legitimacy can be overcome provided that a 'new' space of legitimacy is constructed, and that ethical rules of participation are respected; ii) the process requires, in addition to extreme flexibility, know-how in facilitating and leading groups; iii) the use of monitoring and evaluation tools in a reflexive way is essential; iv) it is beneficial, by choosing the right modelling tools, to combine qualitative and quantitative criteria of assessment.

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