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Research Paper

Participatory modelling for agroecological transitions: Engaging stakeholders in transformative pathways

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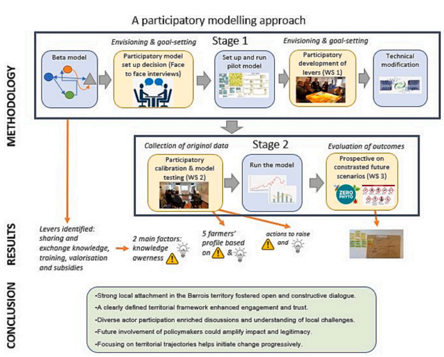
HIGHLIGHTS

- Participatory modelling improves calibration and coherence of the research model.
- Workshops enable collective reflection and strengthen connections between actors.
- Territorial levers emerge: awareness, renewed training, advice, and informal exchange.
- Transition requires involvement of researchers, consumers, and policymakers.
- Brainstorming on trajectories supports shared reflection on the territory's future.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The worldwide use of synthetic pesticides has been rising for decades. Agroecology offers a promising alternative, but its adoption requires support from public policy and multi-scale institutional and social levers. Recent policy approaches integrate levers promoting collective and territorial collaboration, recognizing the local scale as crucial for agroecological transitions. These levers involve mobilizing territorial stakeholders and implementing context-specific levers.
OBJECTIVE: Our objective is to better understand territorial levers that support agroecological transformation and associated practice change dynamics. We engaged with stakeholders using a generic territorial socio-ecological model to identify local levers and potential agroecological transition pathways.
METHODS: In the Barrois region (Eastern France), a participatory modelling initiative involved stakeholders from a farming territory aiming to reduce pesticide use. Three participatory workshops were organized to: (1) identify context-relevant levers; (2) calibrate the model based on the territory's current state; and (3) explore agricultural trajectories and supporting levers.
RESULTS AND CONCLUSIONS: The use of the model highlights the dynamic and multi-factor nature of transitions. The workshops fostered rich dialogue and proposals, playing a central role in co-construction. Participants collectively identified levers such as awareness-raising, training initiatives, new stakeholder networks, and

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evolving advisory services. However, these levers vary depending on farmers' sensitivities and production types. Discussions emphasized the importance of involving not only farmers but also consumers and supply chains to drive change.

SIGNIFICANCE: This participatory approach produced a more realistic model and created learning opportunities for all participants (researchers and agricultural stakeholders), despite challenges like communicating complex theoretical concepts and vocabulary.

1. Introduction

After the Second World War, agricultural modernisation was levered in Europe. To increase productivity, it promoted enlarging farms and fields, genetic selection, and the systematic use of synthetic fertilizers and pesticides. Since then, the worldwide use of synthetic pesticides has risen sharply (FAO, 2022; Özkara et al., 2016). Nevertheless, this use has been a complex and controversial subject for several decades, involving diverse stakeholders. It is in especially criticised for its environmental and health impacts (Aktar et al., 2009; Batsch, 2011; Frische et al., 2018; Leenhardt et al., 2022).

For over 15 years, European Union policies have promoted pesticide reduction (e.g., European Directive 2009/128 on the "sustainable use of pesticides", legislation banning neonicotinoids in 2018, the "From farm to fork" 2020 strategy). In France, the *Grenelle de l'environnement* in 2007, a series of meetings to define long-term environmental decisions, was followed by legislation to put them into practice. Various regulations (global lever plans to reduce the use of glyphosate, ban on neonicotinoids in 2018) and three successive national Ecophyto agricultural plans to promote a reduction in the pesticide use have emerged.

The third plan, Ecophyto II+, aims to reinforce the levers of the previous plans (e.g., bio-aggressor monitoring networks, knowledge of plant protection products, organic farming) by integrating new levers promoting collective and territorial collaboration. These levers include the mobilisation of territorial stakeholders and the implementation of the plan at local scale (awareness-raising, training, farm diagnostics, reduction plans, technical support, etc.). The aim is to promote local ownership while taking into account the constraints and opportunities specific to each territory (Ministry of Ecological Transition, 2018).

At the territorial scale, agroecosystems encompass various environmental, economic, and social aspects that interact in complex, non-linear way (Darnhofer et al., 2010; Gunderson and Holling, 2002; Wezel et al., 2020). Reducing pesticide use thus requires considering these interconnected dimensions simultaneously (Lescourret et al., 2015; Rebaudo and Dangles, 2013). In order to gain a better understanding of the dynamics of changing practices on a territorial scale, we have built a socio-ecological modelling framework of a territorial socioecosystem (Bourceret et al., 2024a). The model aims to study the impact of combinations of territorial levers on trajectories of agricultural practices. This agent-based model simulates both farmers' decision and crop disease dynamics and yield. Farmers' behavior in choosing practices depends on factors such as their own profit, their neighbors' profit, and their sensitivity. Thus, they respond to territorial levers that affect either the disease level (ecological levers, such as the establishment of hedgerows) or their profit (economic levers, such as pesticide prices). Consequently, simulated practices trajectories vary depending on appliers levers. By integrating ecological, economic, and social aspects, the model provides valuable insights into agroecosystem dynamics. Our objective was to use this research model within a participatory modelling, rooted in a specific territory, to improve the model and foster reflection and engagement regarding pesticide reduction pathways.

Different studies highlight the value of involving stakeholders in developing and calibrating models addressing changes in agricultural practices (Barnaud et al., 2013; Farahbakhsh et al., 2025; Hewitt et al., 2014; Voinov et al., 2016). Participatory approaches have gained growing interest in recent decades (Barreteau et al., 2013). This approach recognizes stakeholder diversity by engaging them as active participants in a cyclical and iterative process combining research, reflection and lever (Mendez et al., 2015). It seeks to include or amplify voices traditionally excluded from research, but directly affected by its outcomes.

As summarized by Voinov et al. (2018), participatory modelling relies on a broad family of complementary methods. Fact-finding approaches, such as interviews, surveys or crowdsourcing, help document local practices and make tacit knowledge explicit. Process-orchestration techniques, including facilitated workshops or role-playing games, structure collective discussions and support the emergence of shared problem framings. Qualitative modelling tools, such as rich pictures, concept maps or causal loop diagrams, are used to visualize system components, articulate mental models and clarify perceived causal relationships. Semi-quantitative approaches, notably fuzzy cognitive mapping, scenario building or multi-criteria methods, allow participants to compare alternative trajectories or examine system responses without requiring full numerical data. Finally, quantitative modelling frameworks, including system dynamics, agent-based models, Bayesian networks or GIS-based analyses, enable the simulation of feedbacks, interactions and spatial or temporal dynamics in support of scenario exploration and decision-making.

The use of one method does not exclude another, and they are often combined and/or sequenced to address the same question, as illustrated in the following examples. Lippe et al. 2018 showed that qualitative soil-fertility information generated through participatory assessments – using reconnaissance survey, semi-structured interviews, field surveys and crowdsourcing via focus group - can be integrated into a spatial land-use model (FALLOW) to explore land-use change dynamics and test management scenarios in data-poor contexts. Bandari et al. (2023) use causal loop diagrams as a central participatory tool to co-identify feedbacks and interactions among sustainability variables with stakeholders, providing the qualitative foundation for the system dynamics model used to explore local Sustainable Development Goals pathways. Moreau et al. (2019) demonstrate how role-playing games (RPGs), combined with participatory mapping and a spatial land-use change model, can effectively capture farmers' decision-making and enrich the exploration of landscape dynamics and management scenarios. Finally, Bandari et al. (2024) integrated participatory scenario building with a locally co-designed system dynamics model to explore how alternative global and local futures shape sustainability pathways in the Goulburn–Murray region. Beyond this overview, our analysis of existing participatory modelling studies also highlights the specific contribution of our approach. We adopted a participatory modelling strategy, hypothesizing that it would foster open and meaningful discussions on agroecological trajectories within the territory.

Participatory agent-based models have been used in various sustainability contexts, yet fewer studies have focused on explicitly structuring farmers' practice-change trajectories from stakeholder-elicited decision criteria and typology, combined with participatory scenario building. We show how different forms of stakeholder knowledge—semi-structured interviews, workshop-derived decision rules, and collaboratively developed scenarios—can be incorporated into the behavioral structure and parameterization of an agent-based model. More precisely, we assumed that working with a research model focused on practice trajectories would improve understanding of their dynamic and interactive nature, thereby enhancing understanding and supporting the transition process.

We present here how we collaborated with farmers and agricultural advisers of the Barrois territory (East of France) (Robert et al., 2024) using a territorial socio-ecological model. Our objective was to work collaboratively and exploratorily on change trajectories, leveraging the territorial model. We developed three successive cooperative workshops, each building on the previous, with the aims of (1) identifying territorial levers tailored to the local context, (2) informing model calibration by defining a realistic initial state of the and (3) proposing agricultural trajectories and reflecting on underlying levers. The workshops included discussions on key territorial features, as well as proposing and exploring levers.

In the Materials and Methods section, we present the study area and the participatory approach. Then, in the Results section, we focus on the outcomes of the brainstorming sessions, emphasizing the territorial levers identified, the model calibration process and the trajectories analyzed according to lever scenarios. Finally, in the Discussion section, we reflect on the processes initiated during the workshops, underlining the benefits of this approach for our case study, and then highlighting the advantages and limitations.

2. Materials and methods

2.1. Study area

The Barrois is a French territory stretching from Aube to Haute-Marne (see Fig. 1). Its most populous city is Chaumont, the capital of Haute-Marne, with 23,666 inhabitants. Agriculture plays a particularly important role in this area, with agricultural land representing more than 50% of the total area of these two departments. The Barrois territory had 440 farms in 2017, including 206 cereal farms and 151 mixed farming livestock farms (Ecochard et al., 2019a). The two types of farms are fairly similar when it comes to cereals, with an average of 170 ha of arable land and an identical distribution of crop rotation, with 80% of the rotation in wheat, barley and oilseed rape. The presence of beef cows is a plus, but has no influence on cereal crops. This small farming region faces varied challenges for its agriculture such as pests, climate change, product prices and soil degradation (Robert et al., 2024). The wheat-barley-oilseed rape system is struggling with agronomic problems, mainly related to weed control and soil degradation. While spending on weed control has increased, the effectiveness of herbicides is deteriorating year on year. In climatic terms, the frequency of weather-related disasters averaged 50% over the decade. The intensity is increasing, and 2016 has become the benchmark, with nearly 7 out of 10 insurance contracts. Less than one farmer in two is covered by weather insurance. Finally, the variation in prices since 2006 has been very significant, and can be as much as double.

The territory is marked by several groups which shape the institutional rural landscape of Barrois: two parks are present in the territory, several groups and cooperatives of farmers and other partners around a common project oriented toward a more ecological and more efficient mode of production (GIEE and CUMA), economically and socially and two Chambers of Agriculture of Haut-Marne and Aube.

2.2. The participatory modelling processes

2.2.1. Participatory modelling approach organized in collaboration with a facilitation engineer within the TRAVERSéE ECOPHYTO project

The TRAVERSéES project (Ecophyto Plan II, 2020–2024), described with some main results in Robert et al. (2024), aimed to explore how various territorial levers can promote a reduction in phytosanitary treatments. The project involved farmers, agricultural technicians, researchers, and engineers in a collaborative approach to conceptualizing the territory and pathways of change. The participatory modelling methodology presented in this article particularly structured these iterative exchanges. The objective of this approach was to work with stakeholders from the Barrois region for a collective reflection on territorial levers likely to encourage changes in phytosanitary practices and transition trajectories.

The development and animation of the workshops was carried out by a trio: a facilitation engineer, Audrey Barbe from LISODE (https://www.lisode.com/); the project leader of TRAVERSéES (Robert et al., 2024), Corinne Robert from INRAE, within which the participatory modelling approach was embedded; and the postdoctoral modeler Amélie Bourceret, responsible for developing the socio-ecosystem model (Bourceret et al., 2024b). This trio enabled the use of appropriate facilitation and

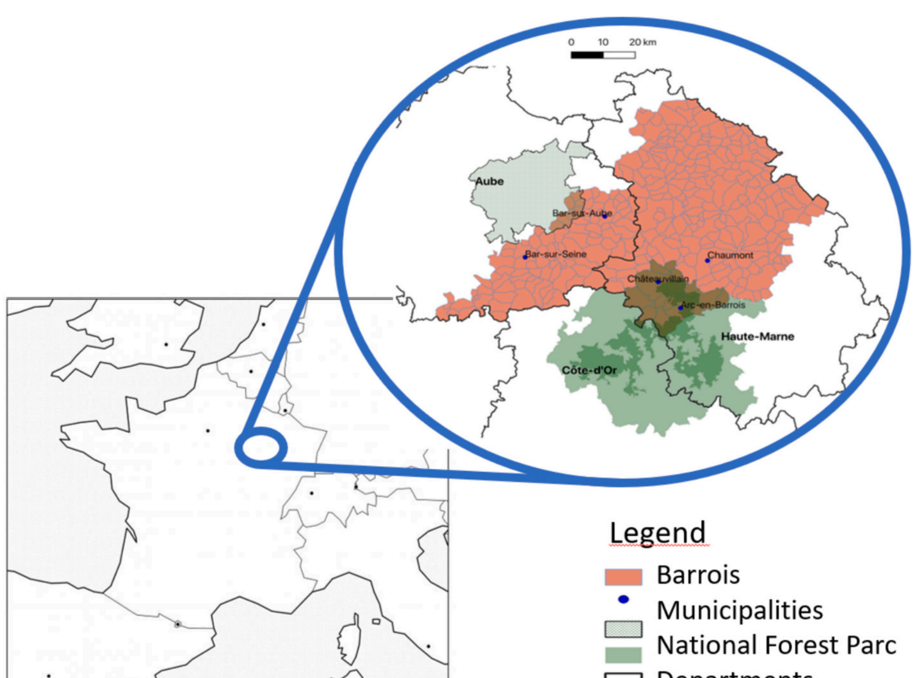

Fig. 1. Map of the Barrois territory (Adapted from Honoré 2020).

consultation techniques, consistent with the project's objectives, while effectively integrating the research model. The preparation of the workshops benefited from several preparatory meetings of the trio, as well as debriefing sessions.

2.2.2. A multi-year participatory modelling process anchored in the territory

This participatory modelling approach involved several iterative phases of exchange with local stakeholders, as well as development and use of the model (see Fig. 2). The process spanned over two years and was characterized by continuous back-and-forth interactions, using a variety of tools to support dialogue and co-construction—both in the field and within the research team. Between the workshops, working meetings were held to align feedback, objectives, and methods, with a strong emphasis on adaptability and on managing the challenging back-and-forth between the research model and the participatory modelling process. The work involved not only dedicated modelling efforts, but also specific preparation for each workshop.

Two main stages can be distinguished. The first stage consisted of envisioning and goal-setting with face-to-face interviews with farmers and with a first participatory modelling workshop. During the envisioning and goal-setting phase, stakeholders can identify the conceptual basis of the model, select the parameters and variables to be included, and, if necessary, modify the topic, underlying concepts, or critical issues to be addressed (Voinov et al., 2016).

The second phase was to collect data to calibrate the model and evaluate the outcomes of scenarios with the model and with stakeholders. In the collection of data, stakeholders are involved in this component as citizen scientists (Voinov et al., 2016). In the evaluation of outcomes, stakeholders are invited to assess the longer-term and broader-scale results emerging from the participatory modelling process (Voinov et al., 2016). In this phase two participatory modelling workshops were conducted to use the model as a tool to support the agro-ecological transition of the Barrois territory.

2.2.3. Stage one: envisioning and goal-setting

2.2.3.1. First model. The first model presented to farmers included agent-farmers' decisions about their own practices (Bourceret et al., 2024a; Bourceret et al., 2023a). Each season, depending on a number of economic and epidemiologic factors, farmers have a probability of changing their practices. A disease spreads into the territory more or less quickly depending on the practices. Farmers receive income based on the chosen practice and the epidemiological status of their plot. The purpose of the model is to investigate how interactions between agent-farmers' behavior and the territorial levers influence trajectories of practices and eventually economic and agronomic territorial indicators. The model results showed that agroecosystems can follow threshold, linear, or more-than-linear trajectories depending on how different factors vary, and that several trade-offs exist among ecological, economic, and agronomic indicators.

2.2.3.2. Face-to-face interviews. Six farmers from the Barrois region were interviewed between November 23 and 25, 2021. Interviews lasted between 1 h 15 min and 2 h (See the interview guide in Appendix 1). Farmers were initially contacted by phone, and interviews were conducted on their farms. They were interviewed to test the main assumptions of the agent-farmers' decision criteria of the model. They were aged between 37 and 54, all had family farms and had worked as farmers solely on their farms. The younger farmers had more education and set up their farm later. They all grow cereals, and half of them also rear livestock. They have between 140 and 380 ha, very few of which they own. The farm employs 2 to 3 full-time equivalents (in two farms, these full-time equivalents include wives). One farmer is an organic farmer, and one is in conversion. They all sell to cooperatives or traders. The organic farmer also does some processing. See in Appendix 2 for more details about farmers. Each interview consisted of three phases: Phase 1 – Presentation of the model; Phase 2 – Semi-structured interview; Phase 3 – Discussion of decision-making factors.

2.2.3.3. Workshop 1 - Definition of territorial levers. The first workshop had several objectives: (i) to get to know one another; (ii) to present the territorial model and explain the concept of territorial levers; (iii) to collectively reflect on relevant territorial levers for supporting the agroecological transition; and (iv) to identify scenarios of levers to be tested with the model for the next workshop. The guiding question was: *"What territorial levers could be considered to encourage changes in plant protection practices?"*

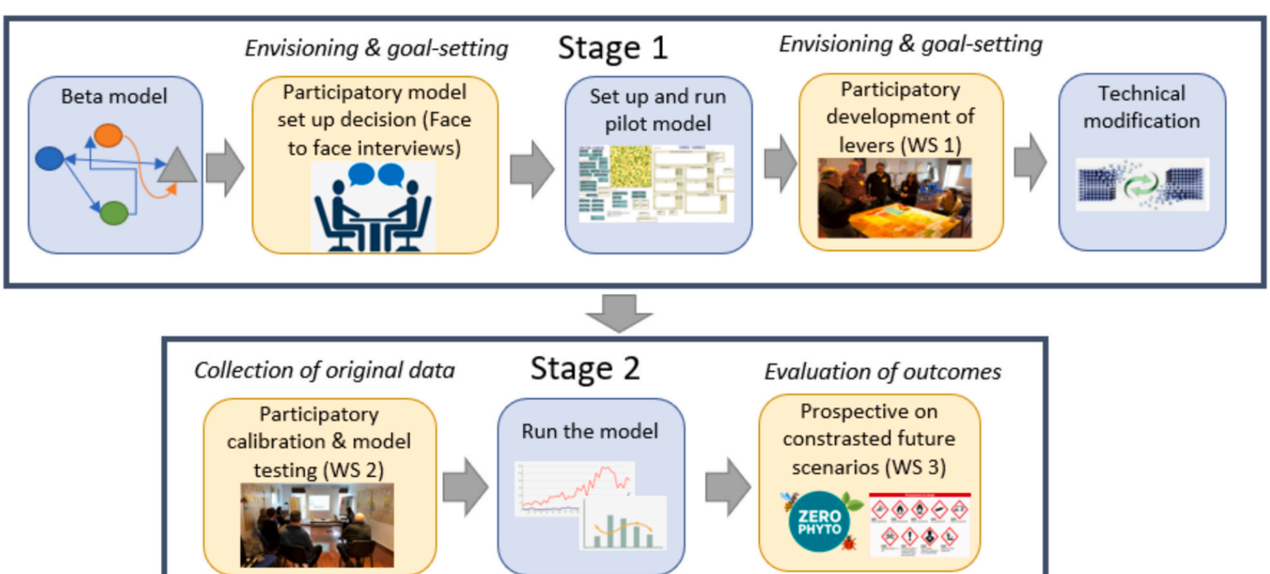

Fig. 2. Steps of the participatory modelling process. The blue boxes represent the steps of computer modelling in the laboratory. Additional preparatory work for the workshops (e.g., alignment of objectives, methods, and content) was conducted but is not shown in the figure. The yellow boxes represent the participatory steps. "WS1", "WS2" and « WS3 » refer to the three successive workshops held in Chaumont with stakeholders. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In preparation for Workshop 1, methodological work was carried out by the organizing team to structure the collective exploration of territorial levers. A detailed analytical grid was developed to guide the discussion and deepen the characterization of each lever. This grid included the following dimensions: "Description of the lever," "Effect of the lever and why," "Origin or impulse of the lever," "Implementation: where and when," "Funding and resources," "Implementation: with whom," "Feasibility (territorial scale)," "Limitations," and "Sustainability." Providing this framework enabled participants to articulate and compare potential levers in a systematic and operational manner.

In addition, the team prepared an introductory presentation situating Workshop 1 within the broader participatory modelling sequence and clarifying the role of territorial levers in the overall process. This preparatory work helped establish a shared understanding of the objectives, enhanced participant engagement, and ensured that the workshop offered a coherent and productive space for collective analysis.

2.2.3.4. Model formulation. The interviews helped us identify the factors that might influence farmers' decisions. The workshop then enabled stakeholders to propose and discuss the types of territorial levers they wished to see represented in the model. By cross-referencing the decision factors identified during the interviews and the levers that emerged during the workshop, we selected the factors most closely related to these levers and changed the model accordingly. Specifically, from the first version of the model (Bourceret et al., 2024a) we kept the epidemiological module and the agronomic representation of practices unchanged, but redesigned the behavioral decision-making module to incorporate the factors highlighted during the interviews and workshops.

2.2.4. Stage two: collection of original data and evaluation of outcomes

2.2.4.1. Workshop 2 – Calibration of the model and discussion of results. The second workshop built on the outcomes of the first and had several objectives: (i) to collectively define the initial conditions of the model to best reflect the Barrois context; and (ii) to collectively discuss and parameterize the selected territorial levers.

This second workshop was the most closely anchored in the model of the three sessions. One of its aims was also to share the modelling experience with participants—particularly the principle of simplifying reality, both in the definition of initial conditions and in the simulation scenarios to be explored. For this reason, the model was presented in greater detail at the beginning of the session.

Between the second and third workshops, the research team ran the model using various scenarios developed during this session. These modelling outputs were one of the elements used to inform and structure the design of the third workshop, which focused on prospective territorial transformation pathways.

2.2.4.2. Workshop 3 – Prospective exploration of contrasting agricultural futures. The third workshop was designed with a forward-looking perspective on the future of agriculture in the Barrois region. Building on the reflections developed during the first two workshops, its objective was to stimulate discussion on different possible trajectories for the territory and to identify the territorial levers likely to support them, as well as complementary levers that could create an enabling environment for their implementation. Central ideas structuring the session included the dynamic nature of change, the activation of levers over time, and the notion of adaptation.

The two contrasting agricultural futures were prepared:

- The "all-phyto" scenario, which envisioned a drastic increase in the use of plant protection products over the next 10 years, farms expansion, a significant decline organic farming, little to no training on alternative practices, strong agricultural specialization, and severe biodiversity loss across the territory.
- The "zero-phyto", scenario, which envisioned smaller and more diversified farm, a large increase in organic farming, new forms of social and agricultural organization, broad stakeholder involvement in training tailored to the local context, restored biodiversity with many semi-natural elements, and public monitoring of farmers' health regarding pesticide exposure.

In the first session, participants engaged with the two contrasting agricultural futures. Using the methodological tools provided, they were asked to address the central guiding question:

"What has happened since 2023 to reach this situation in 2035?"

They explored the key questions of *"What happened?"* and *"Who was involved?"* and produced both graph-based representations of temporal trajectories and a narrative reconstruction of the sequence of events, actors, and mechanisms shaping each future. This dual use of graphs and narrative helped participants explicitly articulate the relationships between triggers, levers, actors, and system dynamics.

In the second session, participants focused on constructing a third, more realistic trajectory, based on their own visions for agriculture in the Barrois. Our intention was that working first with highly contrasted, deliberately extreme futures would expand their imaginative space and facilitate a more open, less constrained reflection when designing a plausible trajectory. This phase encouraged participants to discuss the timing and interplay of levers, the conditions required for change, and to develop a shared narrative describing a feasible transition pathway for the territory.

2.2.5. Organizational aspects of workshops

The first two workshops were deliberately conducted twice— once with a group of farmers and once with a group of professional agricultural organizations (APOs)— based on the hypothesis that this would allow each group to speak freely and avoid possible risks of self-censorship in mixed settings. This also allowed us to capture distinct viewpoints and identify where perspectives converged or diverged. In contrast, Workshop 3 brought all participants together in a single group. By that stage, participants were more familiar with the project and with each other, and we considered that a joint discussion would foster richer exchanges, comparison of viewpoints, and collective sensemaking.

We aimed to bring together farmers with diverse profiles — in terms of farming systems, types of production, and age. The group of farmers consisted of seven farmers and one agricultural engineering student. They represented several types of agriculture: conventional agriculture, soil conservation agriculture, organic agriculture, and sustainable agriculture. Some farmers are solely involved in field crops, while others are involved in field crops and livestock farming. Some are members of exchange networks (for equipment, experimentation). The same approach was applied to the selection of agricultural advisors. The seven advisors came from the following institutions: Regional CUMA Federation, Livestock Farmers' Representative, Organic Farming Advisor, Chamber of Agriculture, National Forest Park, Agricultural College, Organic Farmers' Association.

The first workshop took place in February 2023, the second in April 2023, and the third in March 2024. Between the workshops, modelling and preparation work was carried out by the research team in order to prepare the next session based on the outcomes of the previous one.

Participants from the first workshop were invited to the subsequent ones. The workshops were held in the study area, in Chaumont, over half a day, in a room reserved and prepared specifically for these sessions, with 6 to 10 participants depending on the session. Each time, we began with an introductory session that included a content presentation, which varied depending on the objectives of the workshop. At the end of each workshop, an evaluation form was distributed and completed by the participants.

3. Results

3.1. Envisioning and goal setting

3.1.1. Testing the coherence of the model's structure and main assumptions

Discussions with farmers about the factors guiding their change-of-practice strategies allowed us to confirm the overall structure of the proposed model and to refine a set of grouped decision-making criteria. For each of five types of factors influencing practice change, we discussed the relevance of the factor with farmers, one by one, and then sought to define corresponding quantitative values or thresholds to implement in the model. Below, we detail the different factors discussed with farmers and the resulting decisions made for the model. For each factor, we have added in parentheses how many farmers agree with the statement made.

3.1.1.1. Economic factors considered. The first factor discussed was profit, considered important by all farmers (mentioned by all farmers). Yet it appeared more individual (mentioned by 5 out of 6 farmers) than comparative (mentioned by 1 out of 6 farmers) and not strongly linked to changes in practices (mentioned by all farmers). Accountants provided average farm data but no benchmarks for alternative systems. For organic farmers, often dependent on subsidies, profit seemed detached from practice. This under-emphasis may also reflect the fact that economic viability is taken for granted and therefore remains implicit rather than stated as an active driver of change. Thus, although profit was cited as crucial, it was rarely the main driver of change; in the model it was kept but only to follow trends. The second factor was market access. Farmers reported no issues selling organic products but saw little opportunity for produce from non-certified pesticide reduction. This absence of a dedicated market led some to doubt the value of such practices, though some would adopt them with support or incentives. We therefore chose not to include this factor in the model for the time being, given the practices considered in this first version.

3.1.1.2. Epidemiological factors considered. In the beta version of the model, we considered the presence of diseases in neighboring plots as a factor influencing pesticide use. Farmers, however, judged this factor to be irrelevant (mentioned by all farmers), as pest and disease pressures vary from ont plot to another and across practices, and alerts issued by cooperatives were seldom used. This also raises questions about how such alerts are actually mobilized in day-to-day decision-making.

Discussions showed that farmers do observe their neighbors' fields, but more as a social than epidemiological cue. However, they remain very attentive to disease pressure within their own plots. They reported adjusting fungicide and insecticide use to pest and disease pressures, while herbicide use remained systematic (mentioned by 5 out of 6 farmers). Since our model does not distinguish between types of plant protection products, we assumed in the model that farmers adjust their plant protection use based on disease pressure (fungal pressure in the model).

3.1.1.3. Social factors considered. Within the category of social factors, three elements were examined. First, peer practices: all farmers acknowledged being influenced by their neighbors, particularly when their practices were perceived as "successful," often evaluated through the visual cleanliness of fields (mentioned by all farmers). This perception is partly linked to epidemiological observations, so the factor was kept in the model as a socially mediated criterion. Second, family influence: rarely mentioned (mentioned by 1 out of 6 farmers) and thus considered not particularly determinant, it was not included in the model for the time being. Third, membership in professional groups: farmers' collectives (equipment-sharing, experimental groups, online networks) fostered openness to new practices (mentioned by 4 out of 6 farmers). This factor was therefore retained.

3.1.1.4. Agronomic factors considered. Regarding agronomic factors, two main aspects were explored with farmers: soil and climatic conditions, and knowledge of alternative crop protection practices. Soil and climatic conditions were frequently mentioned as important considerations when choosing insecticides or herbicides (mentioned by 4 out of 6 farmers).

Knowledge was considered essential. Farmers most often cited experience—both their own and that shared by other farmers during discussions— as well as observation as key sources (mentioned by 5 out of 6 farmers). Although conventional agricultural training was also mentioned, it was more viewed as secondary (mentioned by 3 out of 6 farmers). Farmers see the acquisition of new knowledge as an essential and ongoing part of their work, particularly through experimentation, which they consider integral to their decision-making process and the choice of practices. In the model, this suggests that knowledge-acquisition levers could be effective and included in the decision process, while acknowledging that forms of knowledge acquisition may be quite plural in reality.

3.1.1.5. Factors related to awareness of the effects of phytosanitary products. Within the category awareness of the effects of phytosanitary products, two elements were considered: pollution (mentioned by 3 out of 6 farmers) and health impacts (mentioned by 1 out of 6 farmers). Concerning pollution, only one farmer referred to air quality and two others mentioned water quality. One of them cultivated a plot located in a catchment area and explained that he would have stopped farming it if compensation had been offered, however since the area was not classified as polluted, he continued his activity. Another farmer carried out tests showing a link between one of his plots and a spring, nevertheless as no pollution was detected, he did not modify his practices. Overall, farmers are aware of soil erosion and potential water issues, but those whose plots have no hydrological connections feel only marginally concerned. This factor can thus be integrated into the model, although its influence is highly dependent on the specific situation of each farm. Health-related concerns were even less frequently expressed: only one farmer reported discomfort due to odors during large-scale spraying, without any change in practices. In the model, these aspects were grouped together under a single factor reflecting awareness of the effects of phytosanitary products. The limited mention of these concerns raises however questions about how easily such issues are discussed in such process.

3.1.2. Identification and discussion of relevant territorial levers

The first workshop aimed to identify potential territorial levers linked to these factors and the appropriate scale of intervention. In the first part of the workshop, participants proposed a wide range of levers during a brainstorming session (see Fig. 3 which shows a result of the brainstorming). Their proposals were grouped into four main categories: sharing and exchange of knowledge, training, valorization, and subsidies.

Knowledge sharing was strongly emphasized. Farmers already engaged in change called for new forms of exchange, including farmer–researcher networks and territorial databases of local experiments, to reduce uncertainty and strengthen collective learning. Sharing equipment and enhancing territorial intelligence were also seen as crucial. For farmers less inclined to change, conviviality and informal exchange were considered more effective entry points. Dialogue between farmers and non-farmers was also highlighted, with the idea of a citizens' convention to foster mutual understanding. Thus, various types of exchanges—related to knowledge, conviviality, territorial issues, and interactions among different stakeholders—were strongly emphasized.

Different types of training were highlighted. First, training on phytosanitary products was identified as an important lever. Farmers stressed the need to raise awareness of health and environmental risks of phytosanitary products. They also emphasized the importance of

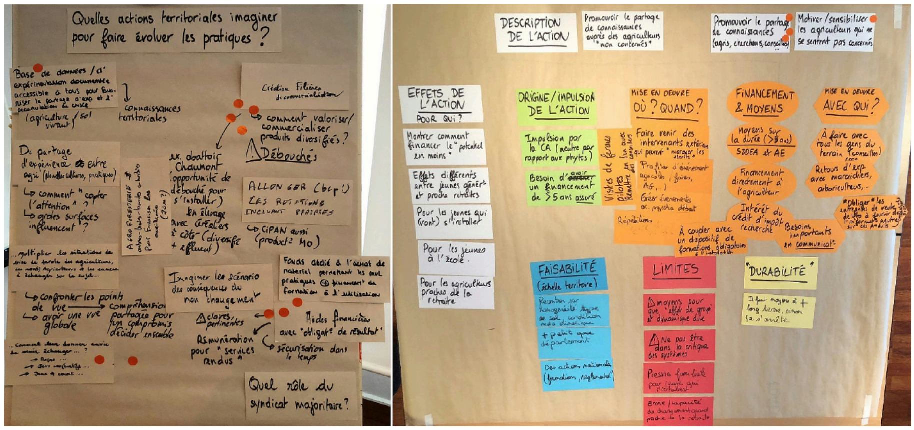

Fig. 3. Selected results from Workshop 1. Left: Brainstorming session during the workshop with APO representatives. Right: Exploration of the lever "Raising awareness among farmers who do not feel concerned."

technical training on alternative practices such as longer rotations, agroforestry, or cover crops. The need for advisors trained in these approaches was also underlined. In this regard, participants tended to favor dialogical and participatory approaches over top-down recommendations.

Economic valorization focused on creating new value chains to support crop diversification. Examples included the development of markets for associated crops to encourage diversification and longer rotations, as well as the creation of a dedicated section in a regional slaughterhouse for animals fed with locally produced plant proteins, thereby strengthening short supply chains and circular agriculture. It is interesting to note that both very concrete and more abstract examples emerged during these discussions.

Finally, subsidies were discussed as essential but in need of clarity, consistency, and long-term vision. Participants noted the importance of linking equipment funding with appropriate training and suggested performance-based aid, rewarding environmental or agronomic services.

In the second part of the workshop, voted for the levers they considered most promising. The Table 1 presents the number of votes for each category of levers. Based on these votes, three levers were then selected for more in-depth work toward their potential implementation. The organizing team initiated a process that required detailing each lever according to the following criteria (see Fig. 3 which shows a result of the exploration): "Description of the lever"; "Effect of the lever and why?"; "Origin/Impulse of the lever"; "Implementation. Where and when?"; "Financing and resources"; "Implementation. With whom?"; "Feasibility (territorial scale)"; "Limits"; "Sustainability". The full details about levers are in Appendix 3.

The first lever focuses on the need to raise *awareness among farmers who do not feel concerned* by agroecological issues. The discussions highlighted the importance of targeting different farmer profiles (young farmers, mid-career, and those close to retirement) and relying on a combination of multiple levers —such as peer-to-peer exchanges, farm visits, external speakers, or events at agricultural fairs. Participants emphasized that such efforts require long-term support (5–10 years) and broad collaboration among advisers, cooperatives, and technical bodies to build trust and gradually shift perceptions.

The second lever proposes to creation of *farmer–researcher networks* and the implementation of experimental research directly on farms. The idea is to jointly test and measure current farming practices under real conditions, in order to produce knowledge that farmers can use to interpret what happens on their own farms and to compare results across the territory. This would constitute a direct interface between research and practice, involving researchers and farmers working together on farms. More concretely, the working group suggested establishing an initial network of about 15–20 committed farmers, collaborating with researchers and students over at least four years, using shared protocols and regular meetings. It was emphasized that such a network would require long-term funding, strong coordination, and close links with existing agricultural organizations to ensure both the dissemination and durability of the results.

The last lever focuses on *developing a local value chain ("Barrois protein")* to strengthen collective organization around plant and animal protein production. The aim is to respond to the growing demand for local and ethical food, improve the valorization of organic and non-organic crops, and support livestock farmers—particularly in pig production. The discussion highlighted the opportunity created by a new slaughterhouse project, which could anchor the initiative and increase processing capacity. Implementation would require an initial diagnostic, the formation of a farmer-led collective (e.g., cooperative or SCOP), and strong collaboration with catering services, canteens, local authorities, and agricultural organizations. Overall, this lever aims to build a territorial protein value chain capable of coordinating production, processing, and marketing at the local level.

Table 1
Number of votes for each category of levers that participants wished to see further developed. An asterisk (*) indicates the levers that have been integrated into the model.

Categories of levers	Number of votes from the farmers' group	Number of votes from the APO representatives' group
Sharing and exchange of knowledge *	6	1
Training about phytosanitary products and alternative practices *	4	2
Economic valorization	1	4
Subsidies	1	3

3.1.3. Identification and discussion of relevant territorial levers

We have cross-referenced the results on the influencing factors identified and the levers to explore in order to choose factors consistent with the levers to be tested. We selected two factors in the representation of farmer characteristics—namely, *knowledge* of alternative practices and *awareness* of the effects of phytosanitary products. These are directly related to the sharing and exchange of knowledge and training on phytosanitary products. This choice is iterative and represents an initial step in the broader modelling process; it illustrates one possible way to integrate stakeholder inputs, while other configurations and modelling pathways remain possible. Fig. 4 illustrates the set of factors and territorial levers raised by participants, highlighting those selected for

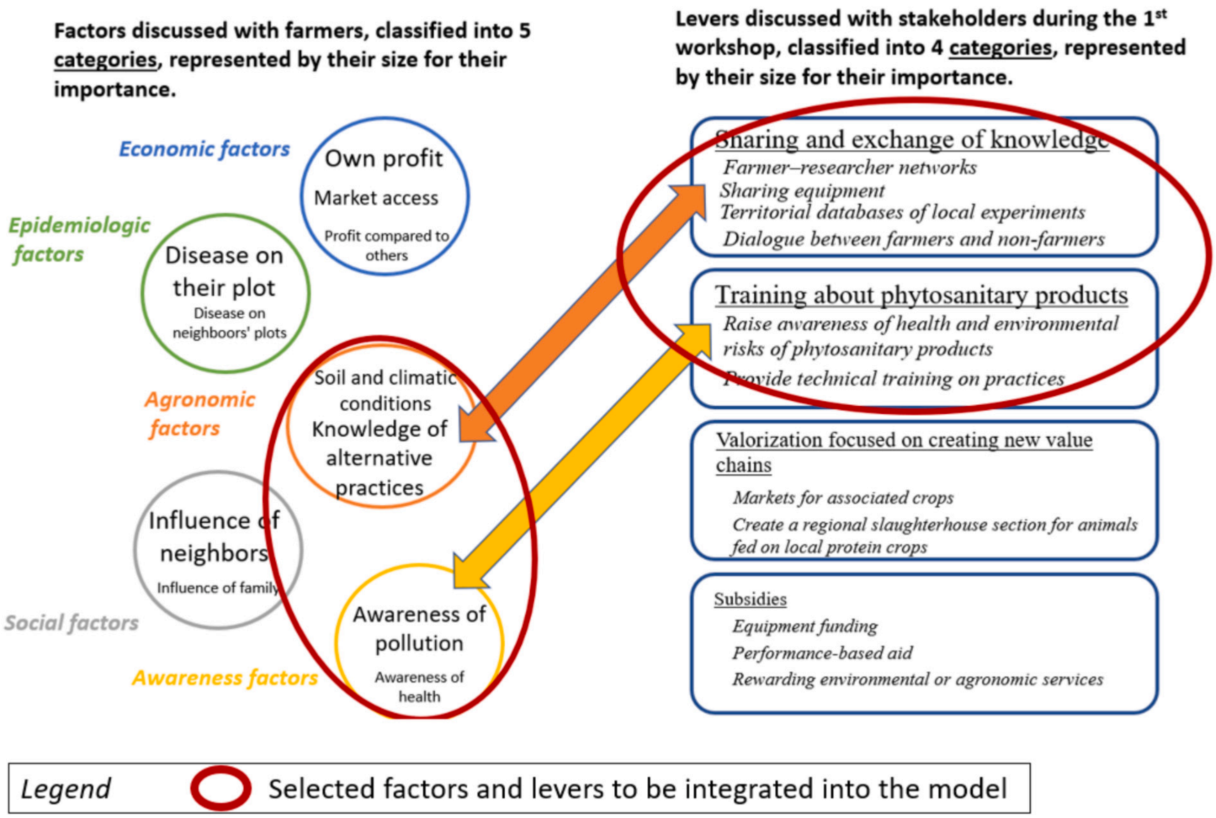

Fig. 4. Factors and territorial levers discussed during individual interviews and the first workshop. Font size reflects their perceived importance. The red circle highlights the levers and factors selected for implementation in the model, as they were identified as both important and interconnected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

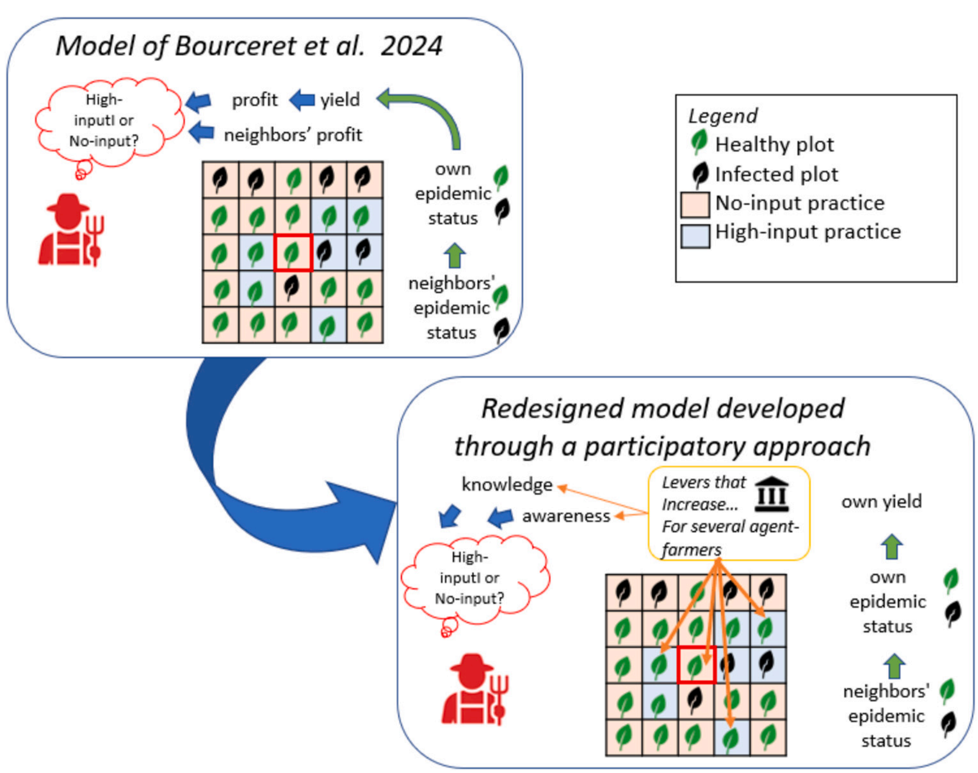

Fig. 5. Visualization of the evolution of the model—from the version presented in Bourceret et al. (2024a) to the revised version produced through the participatory process—highlighting the main structural changes.

integration into the model.

Moreover, due to the very nature of modelling, we had to simplify the representation of the territory. This led to rich and engaging discussions. In order to better understand the influence of the two factors on decision-making, as well as the potential levers to act on them, we deliberately chose to not to account for the effect of other variables (e.g., economic constraints and epidemiologic constraints). Fig. 5 provides a visualization of the model from the version presented in Bourceret et al. (2024b) to the revised version developed through the participatory process and illustrates the main differences between the two models.

3.2. Model formulation

In the model, the agent-farmers must choose between two practices: no-input (NI) or high-input (HI). Each season, depending on their *knowledge* of alternative practices and *awareness* of the effects of phytosanitary product, agent-farmers have a more or less significant probability of changing their practices. Territorial levers can be put in place and influence knowledge and awareness. Furthermore, agent-farmers are influenced by their neighbors. The purpose of the model is to investigate how interactions between agent-farmers' behavior and the territorial levers influence trajectories of practices end eventually economic and agronomic territorial indicators. Appendix 4 presents a description of the practices, a list of input and output variables, and their unit of analysis.

3.2.1. Farmers decision-making

The core of the agent-famers' decision-making is the probability of change $p_{i,t}^{HI\to NI}$ for an agent-farmer *i* from its farming practice *HI* to a farming practice *NI* in year *t* (see Eq. (1)). A probability of change equal to 0 represents no interest to change and a probability to change of 1 represents a full interest to change.

$$p_{i,t}^{HI\to NI} = \begin{cases} 0 \text{ if } \chi_{i,t}^{HI\to NI} < v_i \text{or } aws_{i,t} < vaws_{i,f} \text{ or } knw_{i,t} < vknw_{i,f} \\ \chi_{i,t}^{HI\to NI} \text{if } 1 > \chi_{i,t}^{HI\to NI} > v_i \\ 1 \text{ if } \chi_{i,t}^{HI\to NI} > 1 \end{cases} \quad (1)$$

The probability $p_{i,t}^{HI\to NI}$ depends the decision-metric $\chi_{i,t}^{HI\to NI}$ and on the factor-metrics $knw_{i,t}$ and $aws_{i,t}$ representing respectively the knowledge of alternative practices of the agent- farmer i in year t and awareness of the effects of phytosanitary product of the agent-farmer i in year t. If this decision-metric is less than the change-practice-threshold v_i of agent-farmers, the probability of change is set to zero. Or, if one of the factor-metrics *is* less than the factor-threshold associated $vknw_{i,f}$ *and* $vaws_{i,f}$ of agent-farmer i for the factor-metrics $knw_{i,t}$ *and* $aws_{i,t}$, the probability of change is set to zero. Agent-famers remember if they wanted to change farming practice the previous year from the current year. The agent-farmer makes only one decision per year. They only change their practice if they want to change two years in a row. This represents the inertia of change. Indeed, farmers have a resistance to change (Anastasiadis and Chukova, 2019). Once an agent-farmer has changed practice, it cannot change again in the following years until the end of the simulation. Indeed, we also assumed that agent-farmers could not return to their previous farming practice given the significant upfront costs (David et al., 2022).

The metric $\chi_{i,t}^{a\to b}$(see Eq. (2)) is composed of two factors affecting farmers' decision-making (knowledge of alternative practices and awareness of the effects of phytosanitary product). It is a weighted sum of the factors-metrics. Defining these factors was at the core of the participatory modelling process.

$$\chi_{i,t}^{HI\to NI} = 0.5 * aws_{i,t} + 0.5 * knw_{i,t} \quad (2)$$

3.2.2. Heterogeneity of agent-farmers

To account for different sensitivities (or cognitive profiles, Meunier et al., 2024; Robert et al., 2024), the agent-farmers are heterogeneous in their decision-making process and their farming practice. They also present distinct profile and belong to various networks. A profile of agent-famers corresponds to a combination of initial factor-metrics shared by a group of agent-farmers (see Table 2). The number of agent-farmers assigned to each profile may vary across profiles. An agent-farmer does not change profile during the simulation. The profiles were defined during the participatory modelling process.

A network of an agent-farmer is the set of farmers in which it is connected. There are different networks in the territory and an agent-farmer can be in various networks. The network can be localised in a specific area or randomly distributed, and the agent-farmers in the network can be all neighbors or with more or less distance between each other's (see Appendix 4.C for details). The sizes of networks are fixed and they can be all different. Agent-farmers with different farming-practice and different profile can be in the same network.

3.2.3. Territorial lever

A territorial lever is defined to potentially encourage agent-farmers to change their practice (see Table 3 for the detailed parameters of levers). They modify a factor in the decision-making of agent-farmers, either their knowledge or their awareness. A lever *Lev* has a number of repetitions *RLev* and an intensity of awareness increase $incS\_L_{Lev}$ and and intensity of knowledge increase $incK\_L_{Lev}$. Defining these territorial levers is at the core of the participatory modelling process. We consider that the effects of the levers may vary across agent-farmers, reflecting differences in farmers' sensitivity to these interventions, with a variability of var_{Lev}. $sizeLev_{Lev,\ RLev}$ agent-farmers are concerned by the lever and are randomly distributed in the grid with a density of $radLev_{Lev,\ RLev}$ from a center of the lever with the coordintate ($xLev_{Lev,\ RLev}$; $yLev_{Lev,\ RLev}$). We describe in the next sections the calibration of the levers.

3.3. Calibration of the model to the Barrois conditions

The objective of the second workshop was to discuss the characteristics of the Barrois region and to identify elements that could serve as initial conditions for our model.

3.3.1. Collective definition of initial conditions

During the workshop, participants created farmer profiles (based on the two previously identified factors, namely, knowledge of alternative practices and awareness of the effects of phytosanitary products) represented in the territory (see Fig. 6).

The discussion led to the definition of five farmer profiles (see Table 4). Profiles A, B, and C represent the majority of farmers in the Barrois region (about 95%). Among these, profiles B and C are present in roughly equal proportions, while profile A is less common. The profiles D and E represent a small percentage of farmers in the region.

Profile A corresponds to farmers for whom arable farming is not the main activity. Their primary production is either a perennial crop (e.g.,

Table 2
Profile of agent-farmers and related variables. P for parameters and V for variables.

Type	Name	Description	Notation	Domain	Unit
P	Profil	Profile of agent-famers as a combination of initial factor-metrics shared by a group of agent-farmers	$prof_{i,t}$	{A,B,C}	w.u.
V	Awareness	Factor reflecting awareness of the effects of phytosanitary products at *t* = 0	$aws_{i,t=0}$	[0; 1]	w.u.
V	Knowledge	Factor reflecting knowledge about the other farming practice at t = 0	$kn_{i,t=0}$	[0; 1]	w.u.

Table 3
Parameters related to the levers.

Name	Description	Notation	Domain	Unit
Lever number	Number of networks	Lev	[1;4]	w.u.
Lever repetition	Number of lever *Lev* repetitions	$RLev$	[0;100]	w.u.
Coordinates of the center of the lever	Ordinate of the center of the lever *Lev* at repetition *RLev*	$xLev_{Lev, RLev}$	[0; N]	w.u.
	Abscissa of the center of the lever *Lev* at repetition *RLev*	$yLev_{Lev, RLev}$	[0; N]	w.u.
Density	Density of farmers in the geographical area of the lever Lev	$radLev_{Lev, RLev}$	[0; 10]	w.u.
Lever size	Number of agent-farmers in the lever *Lev*	$sizeLev_{Lev, RLev}$	[0; 10]	w.u.
Increased awareness due to the lever	The increased awareness due to the lever Lev	$incS\_L_{Lev}$	[0; 1]	w.u.
Increased knowledge due to the lever	The increased knowledge due to the lever Lev	$incK\_L_{Lev}$	[0; 1]	w.u.
Lever variability	Variability of leverage effects on awareness and knowledge	var_{Lev}	[0; 1]	w.u.

grapes) or livestock. They devote less time to arable crops than the other profiles and typically have a relatively high level of pesticide use. In Haute-Marne, they are predominantly mixed crop–livestock farmers, whereas in Aube they are mainly winegrowers.

The profile B and C are farmers followed by a technician. But they are divergent in the origin of technician: from the Chamber of Agriculture (profile B) or from cooperatives (profile C). The level of knowledge of farmers in these profiles reflected the level of knowledge of the technician following them. As well as the level of reduction of pesticides depends on the technician. The technicians of the profile B tend to be "neutral" technicians. The technicians of profile C are both sellers and buyers. The reduction dynamic will depend on confidence in the technician.

The profile D represents farmers who are curious, who experiment, who are prepared to take risks. Their level of use of plant protection products varies widely, with some farmers having a rather high level and others a rather low level. Despite these differences, this group is considered to have a high level of knowledge and awareness.

Profile E groups together farmers engaged in extensive systems, characterized by relatively low input use and a focus on moderate performance.

To simplify the model and its interpretation, we ultimately chose to retain the three profiles that are most represented in the territory (Profiles A, B, and C). At the beginning of the simulation, farmer-agents are randomly assigned one of these profiles, in proportion to their occurrence in the region. Each agent is then attributed an initial level of knowledge and awareness consistent with its assigned profile.

3.3.2. Collective definition of awareness-raising and knowledge acquisition levers

Different levers were described and calibrated during the workshop 2: groups of farmers experimenting together, thematic visits, high level training Certiphyto and a stand in an agricultural show. Table 5 gives more details on the model specification for these levers.

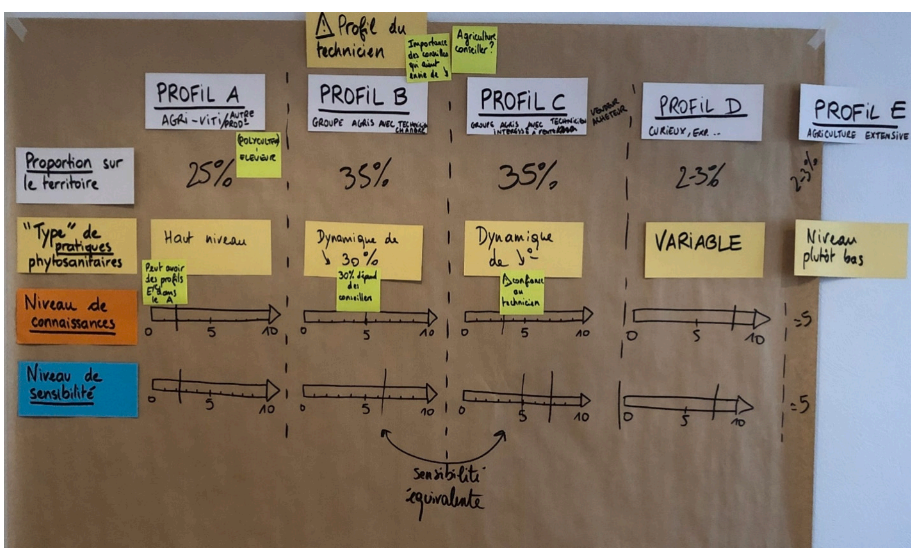

Fig. 6. Results of profile calibration during the workshop.

Table 4
Results of profiles of farmers in Barrois.

	Profile A	Profile B	Profile C	Profile D	Profile E
PROFILE DESCRIPTION	Farmers – winemakers / Farmers - breeders Field crops are not the main production	Farmers followed by a technician from the Chamber of Agriculture, for example	Farmers followed by a technician interested in sales	Farmers who are curious, who want to experiment, who are prepared to take a risk to try things out	Extensive farmers
PROPORTION IN THE AREA	25%	35%	35%	2–3%	2–3%
LEVEL OF USED OF PHYTOSANITARY PRODUCTS	High level of use	Reduction dynamic of around 30%	Reduction dynamic	Variable (both high and low level)	Rather low level
LEVEL OF KNOWLEDGE	2–3/10	5/10	2–3/10	8–9/10	5/10
LEVEL OF AWARENESS	2–3/10	6–7/10	6–7/10	7–8/10	5/10

Table 5
Specifications for the model of levers to raise awareness and knowledge acquisition.

Lever	Group of farmers who experiment together	Thematic visits	High level training certiphyto	A stand at an agricultural show
WHERE IN THE AREA?	Rather dense	Geographical proximity / contextual / production / practice	Everywhere	Everywhere
TOTAL NUMBER OF FARMERS INVOLVED	Approximately 50 to 75 farmers (if we imagine 3 groups)	. Approximately 10–20 (Depends on the theme, production, etc)	10–20 per session	Large number
IMPACT ON INCREASING THE LEVEL OF KNOWLEDGE	Approximately 8–9 / 10	Between 5 and 10 / 10	Approximately 5 / 10	Between 0 and 2 / 10
IMPACT ON INCREASING AWARENESS	The increase depends on the technician	Between 5 and 10 / 10	Very variable	Between 0 and 2 / 10

The group of farmers experimenting together is a group of farmers that share similar issues with same(s) crop(s). Similar soil and climate conditions (mainly linked to geographical proximity) are often a pre-requisite. The snowball effect on the other participants in the group is important.

But the diffusion has to spread out of the group. Thus, thematic visit may be organized, with demonstration and discussion. They would then be relevant if they could be open to farmers other than those who are experimenting together, and dedicated to a subject, a specific problem which may concern these other farmers.

A lever with a broader scope was proposed, to have a stand in an agricultural show. The agricultural show could certainly reach people, but that the effectiveness (in terms of impact on the level of knowledge and awareness) are very weak. Additionally, these agricultural shows attract certain generations, not younger ones.

Finally, a high-level training related to the use of phytosanitary products could raise the awareness of farmers. Currently, Certiphyto training is compulsory for all farmers, and the content seems poorly adapted to the real needs of farmers. Participants was in favor of a training more interesting, more substantial field parts and more locally anchored (to be more coherent with the problems of farmers on their land).

3.4. *Sensitity analysis and scenario's simulations*

Given the structural changes made to the initial modelling framework, it is not possible to reproduce the results obtained in the original version of the model. The updated model focuses exclusively on decision factors related to farmers' sensitivity and knowledge—two elements that directly emerged from the participatory process. To assess the robustness of this revised model, we conducted a dedicated sensitivity analysis examining the influence of key parameters on model outcomes based on the calibration of the previous steps (see Appendix 5 for the datasets). The results of this analysis are provided in Appendix 6.

The sensitivity analysis revealed that several distinct combinations of parameter values can generate system trajectories consistent with a "zero-phyto" and "all-phyto" pathways. For example, we present in Fig. 7 the result of a parameterization with 20 repetitions per lever with a density of 100. This plurality of plausible configurations indicates that the model can reproduce different behavioral patterns leading to similar long-term outcomes.

Based on this modelling work and with a forward-looking perspective, we chose to explore two particularly contrasting scenarios — an "all-phyto" trajectory and a "zero-phyto" trajectory — which served as reference frameworks for the discussions in Workshop 3. In the workshops, the aim was not to determine a single "correct" parameterization, but rather to examine these trajectories with stakeholders and discuss their views on how such outcomes could realistically be reached. This approach was intended to explore the diversity of pathways envisioned by participants, the conditions they considered necessary for each, and the underlying mechanisms they perceived as driving change. In doing so, it opened the way for reflection on adaptive and territorially grounded transformation processes.

3.5. *Prospective transition trajectories*

The third workshop was designed with a forward-looking perspective on the future of agriculture in the Barrois region. The aim was to

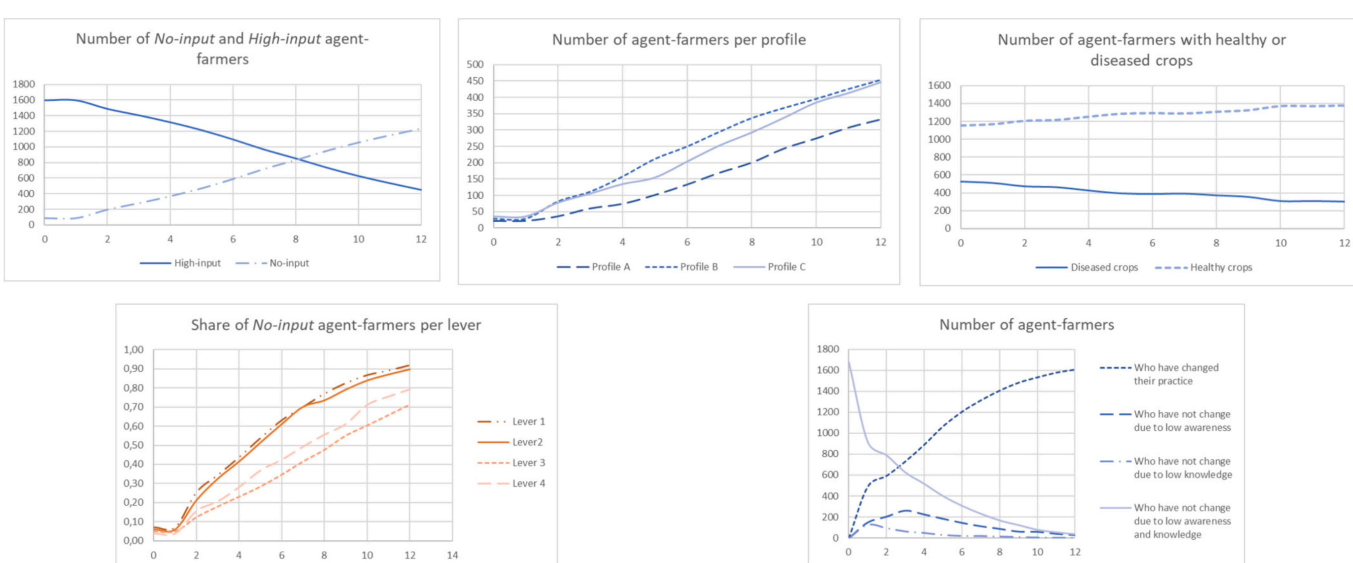

Fig. 7. Illustration of a possible pathway and associated output data for the Zero-phyto scenario. Results are shown for selected indicators using the parameterization.*RLev = 20, radLev = 100, radS = 3, radK = 3, incS_N = 0.1 and incS_K = 0.1.*

stimulate discussion on possible trajectories for the territory and to identify territorial levers that could support such futures. In this context, participants first explored two contrasting agricultural futures presented by the organizing team and were invited to answer the question: "What has happened since 2023 to reach this situation in 2035?" The objective was to identify the key events, levers, and actors that might have shaped each of these futures. Two different groups explored the trajectories according to their interest.

During discussions on pathways of change, participants were proposed to answer the questions of "what?" and "who?" is involved in the transformations depicted in the "all-phyto" trajectory. To focus attention on trajectories themselves, they were also proposed to work with producing graphs representing the evolution of different variables over time.

3.5.1. "All-phyto" trajectory

For the "all-phytos" trajectory, participants identified several triggering events: a decrease in prices of chemical inputs; changes in market prices for organic and conventional products favouring conventional production; increased CAP subsidies benefitting larger farms; an upsurge in retirements; technological advances suited to large fields; and a decline in the availability of trainings on alternatives practices. Regarding the social context, participants suggested that these triggers would occur in a situation marked by a deep divide between farmers and civil society, as well as reduced regulatory constraints on pesticides. Additionally, developments in the industrial sector were perceived as promoting industrial production and influencing collective catering. During discussions about the trajectories of change, participants explored the questions of "What?" and "Who?" were implied in the changes occurring within the "all-phytos" trajectory.

Working on graphs representing the evolution of different variables over time opened the way for deeper reflection on possible system dynamics. The group spent time discussing how to depict these dynamics, which was precisely the intention of the exercise. The graphs (shown in Fig. 8) illustrate, for example, the evolution of pesticide use alongside variables such as the number of farms, technological progress, and the role of advisory services. The choice of variables to to represent proved particularly important as it helped to interrogate the relationships between triggering events and trajectory dynamics. A notable aspect of the discussions concerned the timing and relative magnitude of the effects attributed to each lever, with participants sometimes finding it difficult to imagine or connect certain effects to specific triggers.

Thus, beyond working solely on an "all-phyto" trajectory, the workshop opened broader questions about how to design trajectories shaped by different levers and associated with different variables.

3.5.2. "Zero-phyto" trajectory

For the "zero-phytos" trajectory, participants identified several triggering events: a reform of the CAP to ensure a guaranteed minimum income for the farmers, and remunerating ecological services; a strong political decision; a a widespread shift in societal awareness; reduced margins for the intermediaries; a combination of a protectionism and an overall environmental considerations in price-setting mechanisms. These triggers were situated within a social context where the population become more conscious of the impacts of farming practices on production Society would remain divided between farmers and citizens, while increased urban-to-rural migration would reshape expectations regarding food and territorial development. Consumers would favor local products, and, public policies would provide stronger support to farmers. Key stakeholders in these changes are the schools and the children, the intermediaries, the civil society and the consumers.

3.5.3. Toward a more realistic trajectory

Based on the discussions of the "zero-phytos" and "all-phytos" trajectories —considered unrealistic because they are too extreme—and reflecting on the links between levers and the timing of changes, participants continued the exercise by focusing on a more realistic trajectory collectively identified, along with the levers needed to promote it.

During this second phase, key levers and actors to mobilize were identified to effectively to effectively support toward the chosen trajectory. Emphasis was placed on collaborative approaches involving farmers, policymakers, advisors, and local communities, highlighting the importance of multi-actor cooperation embedded in the territory for envisioning the Barrois agricultural future. Discussions also underlined the need for clear communication, continuous training, and adaptable financial incentives to support sustained changes. Together, these elements form a shared narrative that can serve as a solid basis for future policy recommendations. A collective proposal to create a periodical in the Barrois was proposed to centralize and popularize local practices and initiatives. Such publication could serve as an 'information bank'

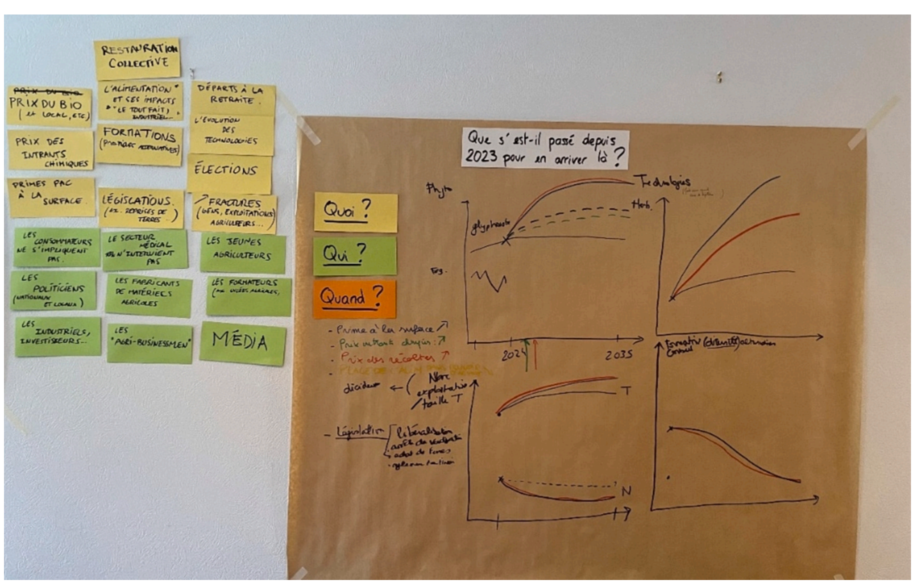

Fig. 8. Photograph of the workshop. On the left, the post-its filled in by participants identifying the "What?" and "Who?" involved in the changes characterizing the "all-phyto" trajectory. On the right, the graphs produced by participants illustrating the evolution of key variables over time: use of phytosanitary products, technological developments, number (N) and size (T) of farms, and training on alternative practices.

enabling farmers to stay informed about existing alternative practices in the territory.

4. Discussion

Our overarching objective was to foster collective exchange, shared reflection, and to initiate a dynamic among local actors around the future of agriculture in the Barrois. We sought to test an innovative participatory modelling approach grounded in continuous back-and-forth interactions between a research-based model and workshops anchored in the territory, in order to simultaneously enrich the model and the stakeholders' discussions. More concretely, our approach aimed to:

(1) identify a range of territorial levers adapted to the local context;
(2) calibrate the model with an initial state reflecting current territorial conditions;
(3) explore and co-construct prospective transition trajectories.

4.1. Discussion of the main contributions of the approach

(1) Stakeholders identified several levers across agronomic, economic, social and financial domains. However, the most emphasized awareness-raising, exchanges and training – are also tied to territorial dynamics. This aligns with studies showing that awareness-raising, training and information are key to changing farmers' practices (Blackstock et al., 2010; Bourceret et al., 2023b; Lastra-Bravo et al., 2015; Okumah et al., 2021). For instance, Barrois Chambers of Agriculture highlight peer-to-peer knowledge exchange and experience sharing (Ecochard et al., 2019a, 2019b), often spotlighting profitable farms using fewer inputs—via longer rotations, crop diversity, cover crops, or conservation agriculture. These promote awareness primarily through financial rather than environmental incentives.

However, workshops revealed the need to integrate non-economic factors that are essential for enabling change: convivial moments such as festive events between farms, knowledge exchange with researchers, and other actors, and health-related aspects through different forms of communication. This multidimensional perspective goes beyond purely economic levers, underscoring the richness of social, cognitive and cultural factors in supporting agricultural transition as emphasized in studies on the adoption of alternative practices (Bacon et al., 2012; Meunier et al., 2024).

(2) The calibration of numerical models is a key challenge (Kersebaum et al., 2015; Liang et al., 2022). Identifying behavioral typologies help understand farmers' responses to change and designing targeted sustainable strategies (Bartkowski et al., 2022). According to Mądry et al. (2013), establishing a clear objective is essential as a first step in creating a meaningful typology. We used first workshop insights to group farmers by knowledge and awareness. Like other European typologies (Bartkowski et al., 2022), we factored in farm' characteristics (type of crop, presence of livestock and use of phytosanitary products. Our profiles echoed classic types: (Burton and Wilson, 2006; Soini et al., 2012), *Innovator* (in our study, profile D) - curious and experimental-; *Productivist* (profile A) - low sensitive and high pesticide use-;; *Environmentalist* (profile B) -higher environmental concern-. However, they introduce the idea of a multiplicity of factors needed to characterize these profiles (social, agronomic, and cognitive characteristics).
(3) The foresight workshop proved to be a generator of diverse and foundational narratives. Starting from highly implausible, extreme scenarios appeared to help participants open up the range of possibilities before later converging toward more concrete and realistic trajectories.

A key element of the process also lay in the use of graphs to visually represent how variables evolve over time. This tangible —though challenging—exercise seemed to help participants better understand and take ownership of the dynamics associated with each trajectory.

Moreover, working simultaneously with several interrelated variables—such as chemical input use, number of farms, technological progress, and advisory services— made it possible to identify interactions within the system. This multidimensional analysis deepened the collective reflection, particularly regarding the timing and impact of different levers, despite some challenges in linking specific effects to precise triggers.

This method resonates with research highlighting the crucial role of social interactions and collective reflection in process of change. Exchanges among participants facilitate awareness of previously implicit patterns of thought (Abric, 2001). Certain factors act as catalysts that ‘unlock’ farmers' openness to alternative practices (Gosnell et al., 2019). Furthermore, articulating an inspiring ‘alternative vision’ is essential to kickstart and sustain the transition. Therefore, the gradual focus on different trajectories, combined with visual aids and analysis of multiple variables, aligns with these findings by fostering shared understanding and allowing new viewpoints to develop.

4.2. The participatory modelling approach implementations: contributions, limitations, and prospects

Several benefits of participatory modelling were highlighted by our study: to reflect deeply and differently on their territory by attempting for instance to represent it realistically within the model; a discussion tool; collective learning and broadening perspectives.

Beyond our case study, agent-based modelling offers important opportunities for analysing transitions in agri-food systems. Agent-based models are particularly suited to represent heterogeneous actors, multi-level interactions, and emergent properties, which are central features of agricultural and food systems where ecological, economic, and social processes continuously interact. Previous work has shown how agent-base models can be mobilized to explore land-use change and territorial dynamics (Hewitt et al., 2014), the dissemination of pest-management innovations (Rebaudo and Dangles, 2013), and the behavioral, ecological and economic components of pesticide-use trajectories (Bourceret et al., 2023a). These studies illustrate the capacity of agent-based models to reveal system-wide effects of interventions, identify leverage points, and examine trade-offs that are difficult to capture with more aggregated modelling approaches. In this sense, our participatory agent-based model contributes to this growing field by integrating stakeholder-elicited decision factors into a dynamic socio-ecological model, thereby opening pathways for future work that couple participatory knowledge with more quantitative scenario exploration.

Based on our earlier model (Bourceret et al., 2024a), several options for testing public policies could have been explored drawing on the literature (e.g., Bemelmans-Videc et al., 2011). Its generic nature, the model is entirely open-ended in terms of the decision factors we aimed to highlight and the levers of public policy we aimed to simulate. By involving local stakeholders in the selection of levers to test, we were able to propose simulations that genuinely resonated with them, and were closely aligned with their local contexts. This approach allowed us to identify realistic, territory-anchored levers that can be meaningfully discussed with policymakers. A key future direction of this work is to engage with policymakers from the outset, in order to co-develop the implementation of these levers and to explore feasible deployment scenarios and their associated trajectories.

Secondly, the model was used as a tool for discussion and for exploring possible territorial trajectories. Although the model presented is a spatialized model, it does not represent the case study region in concrete terms. However, its genericity did not hinder discussions. In fact, the abstraction provided by the research model may have even stimulated dialogue, by distancing the discussion from a real and sometimes conflictual object. The third and final workshop was a success in this regard.

Participatory modelling has thus not only produced simulation results, but also fostered exchanges and collective reflection. It is possible that these exchanges were reinforced, by the three-following-workshop approach we adopted, which allowed participants to gradually get to know one another and build relationships over time. As a result, this successive workshop method—although challenging to organize—proved to be a powerful driver for in-depth dialogue and network-building among participants.

Finally, an important aspect of the participatory modelling is learning (Voinov et al., 2018). Some farmers were unfamiliar with certain alternative practices discussed in the workshops, or with the range if opinions that others might held about them. Farmers and farmers' organizations also had the opportunity to discover modelling as a tool and to demystify digital models. Working with the research model also allowed discussions around specific ecological processes—such as the spread of fungal spores in an agricultural landscape—drawing on our work on landscape-scale epidemic modelling (Précigout et al., 2023).

For researchers, the process was equally enriching. It provided valuable insights into local practices, field realities, stakeholder perspectives and the roles played by different actors in the territorial area. Two examples stand out: (i) the relative difficulty or feasibility of implementing certain levers over others and the perceived hierarchy among them, emerged as important forms of knowledge. (ii) The dynamics of how farmers interact and influence one another in adopting practices proved especially interesting.

Once again, this mutual learning was probably greatly enhanced by the three-step workshop approach, which allowed for clarification and deepening of key issues from one session to the next. Moreover, the alternation between workshop sessions and laboratory work (used for instance to refine the model and simulations) proved to be also valuable in supporting a long-term, iterative process that evolved over time. The quite long temporal dimension is therefore central to the proposed overall approach.

However, the participatory modelling approach has shown several difficulties. First, as many qualitative methods, it is time-consuming, and highly participative, requiring a strong commitment from the participants. As highlighted by Naulleau et al. (2022) engaging stakeholders is a significant challenge. In our case, each session required participants to be involved for half a day - given the complexity of the topics discussed (e.g., definition of farmers' profiles and calibration of levers for instance), and to attend up to three workshops. We had to strike a balance between the number of people we aimed to involve and the information we aimed to obtain. Although we ideally wanted the same group of stakeholders to attend all three workshops, we were unable to bring exactly the same participants together each time, due to scheduling constraints, despite their expressed interest in the project.

Secondly, we observed a self-selection effect among participants. Although we reached out to a broader pool, most of those who chose to attend were already engaged in ecological approaches, either as farmers or through their roles in professional agricultural organizations. This highlights a central issue: the diversity of participants. How can we design and implement an inclusive method? How should we communicate and recruit—and through whom? These are fundamental questions for broadening participation and ensuring a variety of viewpoints are represented.

A third difficulty involved defining key concepts—such as “awareness” and “knowledge”—as factors in farmers' decision-making. We chose these terms because they captured many of the issues discussed during the workshops, but they remain broad and open to varying interpretations. It is therefore essential to begin by clarifying the meanings of such terms with participants, to ensure that the results reflect shared understandings and intended outcomes.

More broadly, the very notion of modelling—what a model is, what it should simplify, and what purpose it serves—prompted important questions from participants, which likely remained partially unresolved by the end of the three sessions. How can a modelling approach be explained—and with what tools—remains a key challenge. These reflections raise broader issues around how knowledge is communicated and open up valuable avenues for future work.

At the same time, it seems equally important to accept a certain degree of ambiguity around some concepts, and to foster a high level of tolerance, inclusivity, and openness throughout the process. Diversity can be a source of richness. Coexistence of differing perspectives should lie at the heart of the approach. The goal is not necessarily to reach consensus or pursue a single common objective, but rather to exchange ideas and broaden individual and collective representations.

Finally, while the outcomes of our participatory approach remain largely qualitative, this work can support more quantitative developments useful for decision-makers. The current study focused on eliciting locally grounded levers and shared representations, but the model could be further calibrated with empirical territorial data (e.g., yields, treatment frequencies, pest dynamics) to strengthen the numerical basis of simulations. Integrating simple economic components would also allow a more explicit assessment of trade-offs and the feasibility of alternative trajectories. In addition, the participatory levers we identified can be parametrized and explored through systematic sensitivity or uncertainty analyses, enabling a more rigorous evaluation of their potential impacts. Such extensions would help transform the exploratory qualitative insights generated here into a more quantitative and operational decision-support framework, while preserving the participatory foundations of the approach.

5. Conclusion — key aspects from our approach: territorial anchoring, actor diversity, temporal dimensions, coexistence of perspectives, working on trajectories

One of the key takeaways from this participatory process was the strong attachment of local actors to the Barrois territory, which proved to be a major asset in fostering rich, open, and constructive dialogue. This deep territorial anchoring facilitated collective reflection and helped build a shared understanding of the region's dynamics, challenges, and opportunities. It greatly contributed to identifying relevant levers for lever and defining realistic transition trajectories.

This experience highlights the importance of carefully defining the territorial framework when designing a participatory workshop. The scale, coherence, and identity of the territory can significantly influence the quality and depth of discussions. In our case, working within a clearly delineated area—where participants shared a strong sense of belonging—facilitated engagement, trust-building, and the co-construction of concrete, locally grounded proposals. This underlines the need to thoughtfully frame the territorial context to create the right conditions for a collective and productive process.

A second key aspect is the diversity of actors involved and the importance of coexistence of perspectives, each contributing and enriching the others. Bringing together varied views enhances debates and deepens understanding of territorial challenges. One promising perspective is to work on these results with public decision-makers. These findings carry a dual weight: that of local actors who select the levers, and that of research validating them. This opens promising avenues for future workshops involving policymakers and citizens, broadening participation and encouraging diverse territorial visions.

In terms of infrastructure, Living Labs (LL) and experimental zones can help address limitations of participatory modelling, such as participation, time constraints, and model complexity. These new ways of imagining participation enable stakeholders to be involved over longer periods, with more assured follow-up thanks to the established infrastructure. This is what the NATAE project aims to achieve, through agroecology-focused Living Labs and the design of bioeconomic models (NATAE, 2025).

To conclude, the long-term nature of the process was valuable. It aligns with the pace and logic of research, while revealing tensions between the urgency of ecological and social transitions and the time needed to implement inclusive participatory processes. In this regard, working on territorial trajectories during workshops enables change without requiring predefined solutions. It helps to steer lever in a positive direction—an essential and adaptive starting point.

CRediT authorship contribution statement

A. Bourceret: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Barbe:** Visualization, Methodology, Data curation, Conceptualization. **C. Robert:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT 4o in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Amelie Bourceret reports financial support was provided by French National Institute for Agricultural Research INRAE. Corinne Robert reports financial support was provided by French National Institute for Agricultural Research INRAE. Audrey Barbe reports financial support was provided by LISODE. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Interview guide (translated from French)

Date:
Start time: End time:

Personal Information

Last name.
First name.
Number of children.
Age
Level of initial education.
Other training/education.
Since when have you been a farmer?
Since when have you been working on this farm?
Is this your parents' or a family member's farm?
If yes, are they still working with you on the farm?
Spouse's occupation.
Other income-generating activities.

Farm Information

Main location (postal code).
Size.
Has the size changed since you took over?
Ownership share.
Number of people working on the farm.
(permanent FTEs, seasonal workers)
Farming systems.
(field crops – cereals, protein crops, oilseeds –, meat production – sheep, cattle –, dairy, vegetable farming, vineyards, etc.)
Changes in farming systems.
Why?

Market Outlets

(direct sales, cooperative sales, tourism, processing, methanation, etc.)
Changes in outlets.

Why?
Farm certification (e.g., Organic, etc.)

Agricultural Practices (technical itineraries)

Crop rotations and species associations.
If cereals:

- How many crops in the rotation?
- What kind of rotations?
- Variety mixtures?
- Species mixtures?
- Changes in number of crops in recent years? Why?
- Changes in rotations in recent years? Why?
- Changes in species and variety associations in recent years? Why?

Soil Management and Fertilization

Share of plowing.
Share of reduced tillage.
Share of no-till.
Evolution of soil management over the past 10 years? Why?
Expected future changes in soil management? Why?

Pesticides

What pest issues do you face?
(aphids, weeds, viruses, fungi – rust, septoria, etc. –, root diseases, fusarium, pests – mice, slugs, etc. –, other insects, etc.)
Main pesticides used (herbicides, insecticides, fungicides)?
Criteria for deciding to treat at the plot level during the season (short-term)?
Criteria for medium-term plant protection strategies (product choice, timing, quantity), equipment strategy, investments?
Changes in number of treatments in recent years? Why?
Changes in types of products in recent years? Why?
Would you like to change anything regarding pesticides? Why?
Have you planned to change anything regarding pesticides? Why?
What alternative practices do you know of?
Do you have the knowledge to implement them?
What types of knowledge are necessary (e.g., discussions with neighbors, training, internet) to adopt these alternative practices?
What difficulties do you face in changing pesticide practices?

Network

Where do you get your seeds?
Fertilizers?
Pesticides?

Do you have exchanges with the following?

Are these exchanges important to you?
What type of exchanges? Technical advice? Sanitary issues? Decisions on plant protection products?

Stakeholder group	Do you have exchanges with them?	Are these exchanges important to you?	Type of exchange (technical advice, sanitary issues, pesticide choices, etc.)
Chamber of Agriculture (CA)			
Neighbors			
Cooperative			
Agricultural traders			
Other organizations			
Farmer groups (associations, working groups, GIEE, CUMA, unions, etc.)			

Miscellaneous

- Would you be interested in receiving the project newsletter?
- Would you be interested in participating in workshops as part of the project?

Appendix 2. Collected data from farmers

Table A2.1
Personal information

ID Farmer	1	2	3	4	5	6
Education	BTS	BEP	Vocational Baccalaureate	BEP	BEP	BEP
Years on the farm	14	28	10	33	26	Always (installed for 30 years)
Spouse's occupation	Off-farm	On the farm	Off-farm	Off-farm	Off-farm	On the farm +10 h off-farm
Other income-generating activities	Yes	No	Yes	No	Yes	No
Farm size incl. Cereals (ha)	350 (250 cereals)	240 (140 cereals)	380	140	300	140 (unknown cereal share)
Size variation	+	+	+	+	=	=
Farming system	Cereals + beef cattle	Cereals + beef and dairy cattle	Cereals	Cereals (+ some laying hens)	Cereals	Cereals + meat sheep
System variation	No	No	No	No (except hens)	No	Yes, sheep for 1 year
Market outlets	Coop/traders	Coop/traders	Coop/traders	Coop/traders + Processing	Coop/ traders	Coop/traders
Outlet variation	No	No	No	Goal: 100% processing	No	Planned (due to organic conversion)
Certification	No	No	80 ha Organic for methanization. “Low-carbon”	Organic	No	Organic conversion since April 2021

Table A2.2
Farm description

Farmer ID	1	2	3	4	5	6
Crop rotation planning	Yes	Yes	No*	No*	Yes	Yes
Variety associations	No	No	Yes	Yes	Yes	No
Species associations	Yes (but limited)	Yes (on livestock parcel)	Yes	Yes	No	Yes (but limited)
Change in number of crops	Yes (+ energy crop)	+	++		+	=
Change in rotations	Dropped rapeseed	Rapeseed if profitable	−		+ due to drop of rapeseed	+ due to drop of rapeseed
Change in associations			++	=	+	
Plowing	0%	20%	0%	0%	0%	50%
Reduced tillage (TCS)	80%	75%	0%	100%	90%	0%
Direct seeding	20%	5%	100%	0%	10%	50%
Past evolution of soil management	- direct seeding	- plowing	- TCS	- direct seeding	=	- direct seeding
Future evolution	+ mechanization	+ plowing	=		+ direct seeding	
Change in number of treatments	+ quantity & frequency	+ quantity & frequency	- quantity & + frequency	−	- quantity & - frequency	−
Change in type of products	- number of different products		−		- (uses dual-active products instead of two separate ones → decrease)	
Would you LIKE to change pesticide use?	=	No	Stop	Return to direct seeding	No	
Do you PLAN to change pesticide use?	=	No	No	No	No	Yes (already changing due to organic)
Knowledge of alternative practices	Organic	More tillage	Compost, essential oils		Mechanical weeding	
Do you have the knowledge?	No		No		No	
Type of knowledge needed	Observation, experiments, training with technician		Discussions with experienced farmers, training		Neighbors, experience. Secondarily: CA & PVA	Took training with PVA, observed neighbors, accounting help
Difficulties in changing pesticide practices	No alternative – if disease hits, pesticides needed	Poor soils + financial difficulties	Nothing available		Time needed, labor issues + equipment cost	

Table A2.3
Agricultural practices (technical itineraries)

Farmer ID	1	2	3	4	5	6
Crop rotation planning	Yes	Yes	No*	No*	Yes	Yes
Variety associations	No	No	Yes	Yes	Yes	No
Species associations	Yes (but limited)	Yes (only on livestock plots)	Yes	Yes	No	Yes (but limited)
Change in number of crops	Yes (+ energy crop)	+	++		+	=
Change in crop rotation	Dropped rapeseed	Rapeseed depending on profitability	–		+ due to end of rapeseed	+ due to end of rapeseed
Change in associations			++	=	+	
Plowing (%)	0%	20%	0%	0%	0%	50%
Reduced tillage (TCS) (%)	80%	75%	0%	100%	90%	0%
Direct seeding (%)	20%	5%	100%	0%	10%	50%
Past evolution	- direct seeding	- plowing	- reduced tillage	- direct seeding	=	- direct seeding
Planned future evolution	+ mechanization	+ plowing	=		+ direct seeding	
Change in number of pesticide treatments	+ quantity + frequency	+ quantity + frequency	- quantity + frequency	–	- quantity - frequency	–
Change in type of products	- fewer different products		–		- (uses products with 2 active substances instead of 2 separate ones → reduction)	
Would you LIKE to change pesticide use?	=	No	Stop	Return to direct seeding	No	
Do you PLAN to change pesticide use?	=	No	No	No	No	Currently changing due to organic conversion
Knowledge of alternative practices	Organic	More soil work	Compost, essential oils		Mechanical weeding	
Do you have the knowledge?	No		No		No	
Type of knowledge needed	Observation, experience, and training with technician		Discussions with experienced farmers, training		Neighbors, experience. Secondarily: Chamber of Agriculture (CA) and PVA	Has done: training with PVA, observing neighbors, help with accounting
Difficulties in changing	No existing alternative: if disease appears, pesticides are needed	Difficult soils + economic challenges	Nothing suitable exists		Labor time, hiring difficulty + equipment costs	

Table A2.4
Network

Farmer ID	1	2	3	4	5	6
Chamber of Agriculture (CA)		Technical advice	Technical advice + Trials	Trials		Training
Neighbors	Labor	Labor, learning		Technical info, varieties, species	Discussions, agronomic advice	Labor
Agricultural traders					Technical advice	
Farmer groups	CUMA		GIEE Apab, social media networks	Dephy Network		CUMA

Appendix 3. Levers described during the in-depth of territorial levers

Three levers have been described during the in-depth of territorial levers.

Raise awareness among farmers who do not feel concerned

Table A3.1
Results of the working group "Raise awareness among farmers who do not feel concerned" (translated).

Description of the lever Effect of the lever	For what purpose?	Origin/impetus for the lever
- Promote the sharing of knowledge among "unconcerned" farmers	- Show how to finance the "potential lost". - Different effects for younger generations and those approaching retirement - For young people who are (going to be) setting up in farming - For young people at school - For farmers close to retirement	- Impetus from the CA (neutral in relation to phyto) - Funding for >5 years is required.
Implementation Where? When?	Funding & resources Implementation	With whom?
- Bring in outside speakers who can "make an impression". - Take advantage of agricultural events, fairs, AGMs, etc. - Create events: screenings, debates - Rehearsals - Visits to pilot farms, linking up with advisers	- Long-term resources (>5 years) SDDEA and AE - Direct funding to the farmer - Interest of research tax credit - To be combined with a compulsory training scheme on setting up - Major communication needs	- To be done with all the people in the field (advisers, cooperatives, etc.) - Feedback from experience with market gardeners, arboriculturists, etc. - Require companies selling pesticides to provide neutral information on these products - > transition to bio-control
Feasibility (regional scale)	Limitations	"Sustainability"
- Refocus on homogeneous soil types and soil and climate conditions - Smaller than department - National actions (training, regulations)	- /!\ means for "group effect" and momentum to last - not to be critical of systems - Family pressure for young people setting up - Desire/capacity for change when close to retirement	- We need more long-term resources, otherwise things will grind to a halt

Carrying out fundamental research on farms

Table A3.2
Results of the working group "Conduct fundamental research on farms" (translated).

Description of the lever Effect of the lever	For what purpose?	Origin/impetus for the lever
- Creation of farmer-researcher networks - Basic research on farms - Using existing farm models - Test things/measure things long term/ innovation - Farm practices: new tests and measurements	- New knowledge - Production of systemic knowledge under real conditions - Provide trends - Compare with other infrastructures, personal decision-making - Agri, agricultural policies, networks - High impact: dissemination of farm and regional results to other farmers	- Existing networks, CUMA? - Initial group - > huge dissemination - Common issue - > pesticide reduction? - How specific is the issue? Ecosystem economics - Diagnosis of issues - > shared issues (territory) - Suggestions on how to work: how to exchange information? - > tools, data
Implementation Where? When?	Funding & resources Implementation	With whom?
- Protocol shared between farmers and researchers - Agricultural measures + researchers - Tools - 4 years x repet, 1 meeting / 6 months - Entire Barrois - Data management - Training on tools - Measurements carried out by farmers/ researchers/students - What feedback? Data analysis - > farmers	- Water Agency, Region, PDR - Researchers: protocol/analysis Beyond that: proportion on … - Farmers: question / plot / measures - Reserve a small plot? rather the system (among farmers)	- Farmers committed, willing, in transition (15–20) - Farmers who don't know each other - Public/private researchers - Schools, universities, agricultural colleges, students - Connection to … - Dissemination - > other networks, validity - Pilot for an "agri-researchers" network
Feasibility (regional scale)	Limitations	"Sustainability"
- Investment 4 years (and more) - Purchase of equipment - Budget? Funding from farmers? - Students - Organization time - Permanent	- Interest, diversity of conditions, real conditions - > + difficult compare analyses - Diversity of measurements - Fate of data - Few/no results - Time, complexity - Links with other players	- Partnership with universities - > project dissemination, students - How long will it last? Long, permanent need INRAE - Very long scale Stage 3, 4 years - > new question - Need for flexibility, help and advice

The protein from Barrois

Table A3.3
Results of the working group "The protein from Barrois" (translated).

Description of the lever Effect of the lever	For what purpose?	Origin/impetus for the lever
- Creation of a sector - > The protein from Barrois - Collective and local organization of the sector - Agri: doing its bit	- Meeting a demand for local and ethical consumption - Promote local supply chains - For AB and non-AB farmers, pig breeders - New slaughterhouse - Multiplicity of animals/animal nutrition	- Slaughterhouse project planned - > supported by the CD - New slaughterhouse - > increased volume - Bring in volumes (pigs) from the region - Difficulty in adding value to AB farm crops - CA initiative: multi-stakeholder discussion (OS, canteens, etc.), promoting AB crops
Implementation Where? When?	Funding & resources Implementation	With whom?
- Initial diagnosis - Possibility of leaving/entering	- PAT: interco, support structures? - Farmers, a "SCOP" or other collective to produce and sell	- Collective catering structures - All those who need protein: livestock farmers, canteens, retirement homes, etc. - Supporting the CA - Associations, farmers' groups, GIEE, etc.
Feasibility (regional scale)	Limitations - Possibility of buying organic / price of organic in a period of inflation - Volumes: sufficient threshold for profitability - Multiple animals - > multiple crops - Competition" effect if a single protein	"Sustainability" - Profitability after a few years

Appendix 4. List of input and output variables

A. Farming practices

We consider two simplified management practices, NI and HI, corresponding to no-input (*NI*) and high-input (*HI*) strategies. These practices are linked to the quantity of pesticide treatments applied, which denotes the number of treatments used by a farmer-agent. The type of practice influences ecological dynamics, particularly disease development. Consequently, yield losses depend on disease infection. The disease escape probability—defined as the probability that the disease does not develop in a field despite infection—is also practice-dependent. More detailed information on these assumptions can be found in Bourceret et al. (2024a).

Table A4.1
Parameters describing a practice a with an epidemic status s.

Name	Description	Domain	Unit
Farming practice	a	{NI, HI}	w.u.
Epidemic status	s	{0,1}	w.u.
Number of pesticide treatments	$q_{a,s}$	{0,1,2}	w.u.
Yield of the field	$y_{a,s}$	[0;1]	w.u.
Disease escape probability	h_a	[0;1]	w.u.

B. Inputs

Table A4.2
Parameters and variables relative to agent-farmers. * P: parameter; V: variables. ^{new}: These are new inputs compared to the previous version of Bourceret et al., 2024a.

Type*	Name	Description	Notation	Domain	Unit
P	Domain size	Number of cells	N		w.u.
P	Change-practice-threshold of farmer	Change-practice-threshold at which the farmer *i* starts to be willing to change farming practice	v_i	[0; 1]	w.u.
P^{new}	Profil	Profile of agent-famers as a combination of initial factor-metrics shared by a group of agent-farmers	$prof_{i,t}$	{A,B,C}	w.u.
P^{new}	Awareness	Factor reflecting awareness of the effects of phytosanitary products at t = 0	$aws_{i,t=0}$	[0; 1]	w.u.
P^{new}	Knowledge	Factor reflecting knowledge about the other farming practice at t = 0	$kn_{i,t=0}$	[0; 1]	w.u.
V	Practice	Farming practice of the farmer *i* in year *t*	$k_{i,t}$	{NI, HI}	w.u.
V	Field epidemic status	Status of the epidemic in the field of the farmer *i* in year *y*	$s_{i,\ t}$	{0; 1}	w.u.
V	Probability to be infected	Probability for the field of the farmer *i* to be infected at each year *t*.	$u_{i,\ t}$	[0; 1]	w.u.
V	Number of treatments	Number of treatments of pesticides used by the farmer *i* in year *t*	$q_{i,\ t}$	[0,1,2]	w.u.
V	Yield	Relative proportion of the maximum potential yield of the field of the farmer *i* in year *t*	$y_{i,t}$	[0; 1]	w.u.
V	Relative proportion of profit	Relative proportion of the maximum potential profit of the field of the farmer *i* in year *t*	$\pi_{i,t}$	[0; 1]	w.u.
V	Escape probability	The probability of the field of the farmer *i* in year *t* to escape from the disease and be healthy	$h_{i,t}$	[0; 1]	w.u.
V	*Profit comparison metric*	*The willingness of the agent-farmer i in year t to have a profit higher than the average profit of other farmers performing the same practice a.*	$\chi_{i,t}^{a\rightarrow b}$	[0; 1]	w.u.

(*continued on next page*)

Table A4.2 (*continued*)

Type*	Name	Description	Notation	Domain	Unit
V	Probability of change	Probability of change of farmer *i* from its practice *a* to the farming practice *b* in year *t*	$p_{i,t}^{a\to b}$	[0; 1]	w.u.
V^{new}	Awareness	Factor reflecting awareness of the effects of phytosanitary products	$aws_{i,t}$	[0; 1]	w.u.
V^{new}	Knowledge	Factor reflecting knowledge about the other farming practice	$kn_{i,t}$	[0; 1]	w.u.

C. Variables related to neighborhood

Table A4.3
Parameters related to the influence of neighbors. * P: parameter; V: variables. ^{new}: These are new inputs compared to the previous version of Bourceret et al., 2024a.

Type*	Name	Description	Notation	Domain	Unit
P^{new}	Neighbors radius for awareness	The radius of influence of neighbors for awareness	*radS*	[0; 5]	w.u.
P^{new}	Neighbors radius for knowledge	The radius of influence of neighbors for knowledge	*radK*	[0; 5]	w.u.
P^{new}	Increased awareness due to the network	The increased awareness due to neighbors	*incS_N*	[0; 1]	w.u.
P^{new}	Increased knowledge due to the network	The increased knowledge due to the neighbors	*incK_N*	[0; 1]	w.u.

D. Output list

Table A4.4
Indicators. ^{new}: * The 1() operator is equal to 1 if the argument is true, otherwise it is 0 (Source: Bourceret et al., 2024a).

Type	Variable observed	Indicators – Average of the last 100 time steps of the simulation	Notation
Farming practices	Farming practice of agent-farmers	Proportion of agent-farmers with no-input farming practice	$\overline{k_t^{NI}} = \frac{\sum_{i=1}^{N2} \mathbf{1}(k_{i,t} = NI)}{N2}*$
		Proportion of agent-farmers with high-input farming practice	$\overline{k_t^{KI}} = \frac{\sum_{i=1}^{N2} \mathbf{1}(k_{i,t} = HI)}{N2}$
	Farming practice of agent-farmers ^{new}	Proportion of agent-farmers with no-input farming practice for the profile *P*	$\overline{k_t^{NI}} = \frac{\sum_{i=1}^{N2} \mathbf{1}(k_{i,t} = NI) \bullet \mathbf{1}(prof_i = P)}{N2}$
		Proportion of agent-farmers with high-input farming practice for the profile *P*	$\overline{k_t^{KI}} = \frac{\sum_{i=1}^{N2} \mathbf{1}(k_{i,t} = HI) \bullet \mathbf{1}(prof_i = P)}{N2}$
Agronomy	Yield of fields	Average yield of all agent-farmers	$\overline{y_t} = \frac{\sum_{i=1}^{N2} y_{i,t}}{N2}$
		Average yield of agent-farmers with no-input farming practice	$\overline{y_t^{NI}} = \frac{\sum_{i=1}^{N2} y_{i,t} \bullet \mathbf{1}(k_{i,t} = NI)}{\sum_{i=1}^{N2} \mathbf{1}(k_{i,t} = NI)}$
		Average yield of agent-farmers with high-input farming practice	$\overline{y_t^{HI}} = \frac{\sum_{i=1}^{N2} y_{i,t} \bullet \mathbf{1}(k_{i,t} = HI)}{\sum_{i=1}^{N2} \mathbf{1}(k_{i,t} = HI)}$
Environment	Pesticides used by agent-farmers	Total number of agent-farmers using one pesticide treatment	$Q_t^1 = \sum_{i=1}^{N2} q_{i,t} \bullet \mathbf{1}(e_{i,t} = 0)$
		Total number of agent-farmers using two pesticide treatments	$Q_t^2 = \sum_{i=1}^{N2} q_{i,t} \bullet \mathbf{1}(e_{i,t} = 1)$
Change	Change of practice	Number of agent-farmers that change their practice	$\overline{k_t^{NI}} = \frac{\sum_{i=1}^{N^2} \mathbf{1}(k_{i,t} = NI) \bullet \mathbf{1}(k_{i,t-1} = HI)}{N^2}$
	Change of practice ^{new}	Number of agent-farmers with profile P that change their practice	$\overline{k_t^{NI}} = \frac{\sum_{i=1}^{N^2} \mathbf{1}(k_{i,t} = NI) \bullet \mathbf{1}(k_{i,t-1} = HI) \bullet \mathbf{1}(prof_i = P)}{N^2}$

Appendix 5. Datasets

NI practices are assumed to be more resistant to pathogens, whereas HI practices achieve a higher potential maximum yield. Consequently, yield losses under disease infection are higher for *HI* than for *NI*. We assume a higher escape probability for the *NI* practice than for the *HI* practice.

Table A5.1
Characteristics of 4 types of field being characterized by: the farming practices High-input (HI) and No-input (NI) and by the epidemics status: 1 being infected, and 0 being healthy (Source: (Bourceret et al., 2024a).

Farming practice	*a*	High-input practice (HI)		No-input practice (NI)	
Epidemic status	*s*	1 (infected)	0 (healthy)	1(infected)	0(healthy)
Number of pesticide treatments	$q_{a,s}$	2	1	0	0
Yield of the field	$y_{a,s}$	0.9	1	0.75	0.8
Disease escape probability	h_a	0.2		0.4	

Table A5.2
Characteristics of agent-farmers at the initialization.

	Notation	Profile A	Profile B	Profile C
Share of agent-farmers		27	36.5	36.5
Awareness	$aws_{i,t=0}$	0.25	0.5	0.25
Knowledge	$kn_{i,t=0}$	0.25	0.65	0.65
localisation			Random	

Table A5.3
Characteristics of the levers.

Name	Notation	*Lever 1 - GROUP OF FARMERS WHO EXPERIMENT TOGETHER*	*Lever 2 - THEMATIC VISITS*	*Lever 3 - HIGH LEVEL TRAINING CERTIPHYTO*	*Lever 4 - A STAND AT AN AGRICULTURAL SHOW*
Lever number	*Lev*				
Lever repetition	*RLev*				
Coordinates of the center of the lever	$xLev_{Lev,\ RLev}$		Random		
	$yLev_{Lev,\ RLev}$				
Density	$radLev_{Lev,\ RLev}$				
Lever size	$sizeLev_{Lev,\ RLev}$	15[a]	30[b]	10[c]	50[d]
Increased awareness due to the lever	$incS\_L_{Lev}$	0.85	0.75	0.5	0.1
Increased knowledge due to the lever	$incK\_L_{Lev}$	0.4	0.75	0.1	0.1
Lever variability	var_{Lev}	0.2	0.4	0.05	0.2

[a] Average of Economic and Environmental Interest Group in France in 2019. Source: https://agriculture.gouv.fr/plus-de-12-000-exploitations-agricoles-engagees-dans-les-groupements-dinteret-economique-et.
[b] Average number of farmers participating in a thematic visit. Source: https://landes.chambres-agriculture.fr/actualites-1/actualite/unite-de-methanisation-a-grenade, https://www.agriculteur-normand.com/des-visites-dunites-pour-preciser-son-projet-methanisation and https://normandie.chambres-agriculture.fr/sinformer/concilier-agriculture-et-territoires/environnement-et-paysages/transition-agroecologique/les-pratiques-agroecologiques-en-normandie/detail-des-pratiques-agroecologiques/visites-dexploitations-en-agriculture-biologique.
[c] Average number of farmers present during a training of CertiPhyto. Source: (Grimbuhler et al., 2024).
[d] Estimated number of farmers going to a stand.

Appendix 6. Sensitivity analysis

We conducted a sensitivity analysis to assess the robustness of key behavioral mechanisms. The analysis focused on characteristics of the decision-making levers that were not fixed during the calibration phase, as well as on parameters governing the influence of neighboring farmers. We did not re-test the elements already calibrated, such as the profiles and the influence of each lever on knowledge and awareness, nor the epidemiological and economic components, since in the current version of the model these components are computed independently and no longer interact with farmers' decision-making processes. For the same reason, the outputs examined in the sensitivity analysis were restricted to variables directly shaped by behavioral dynamics—namely, the number of farmers adopting each practice (NI or HI) and their distribution across the different decision-making profiles.

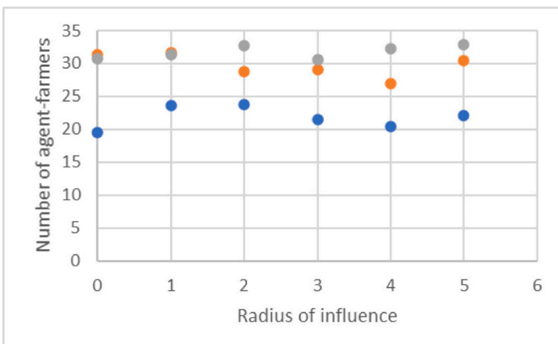
For reasons of space, we only present a subset of these results in the manuscript.

Effect of neighbor-related parameters

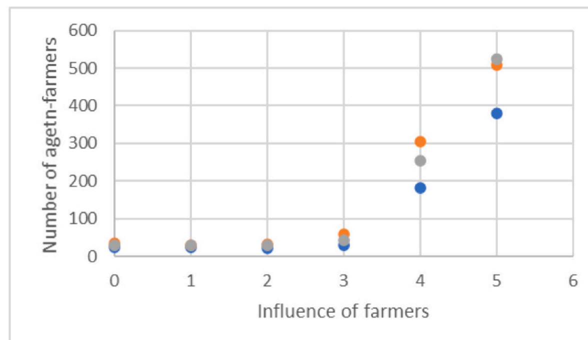
To assess the influence of the parameters associated with neighbors, we first neutralized the effect of the levers. Since both *knowledge* and *awareness* require a minimum value of 0.5 (out of 1) to trigger a change in practice, we examined their diffusion within the neighborhood by varying them separately: when testing the diffusion of *knowledge*, *awareness* was kept constant and set above the threshold, and vice versa.

In addition, we tested two key characteristics of neighbor influence: (i) the radius within which neighbors can affect an individual farmer, and (ii) the intensity of this influence. This allowed us to isolate and evaluate the specific contribution of each neighbor-related parameter.

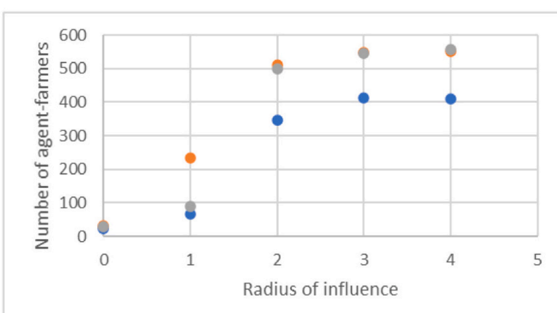
By varying the intensity of the increase in *awareness* or *knowledge* generated by neighbors, we observe that when neighbor influence is set to zero, the number of agent-farmers remains constant at its initial level, regardless of the radius of influence. When neighbor influence is set to 0.1, 0.5, or 1, the number of agent-farmers adopting the practice consistently converges toward a plateau below 600. However, the speed at which this plateau is reached increases with the strength of the neighbor-driven increase in *awareness (see Fig. A6.1)* or *knowledge* (see Fig. A6.2).



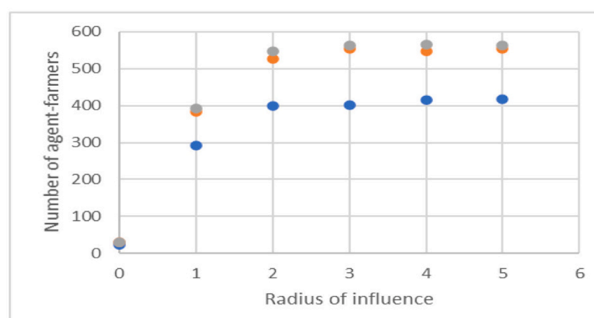
Increased awareness due to the network, *incS_N=0*



Increased awareness due to the network, *incS_N=0.1*

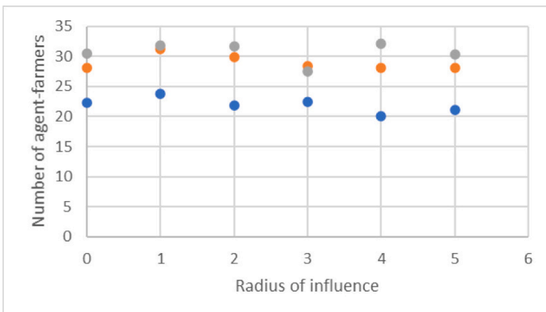


Increased awareness due to the network, *incS_N=0.5*

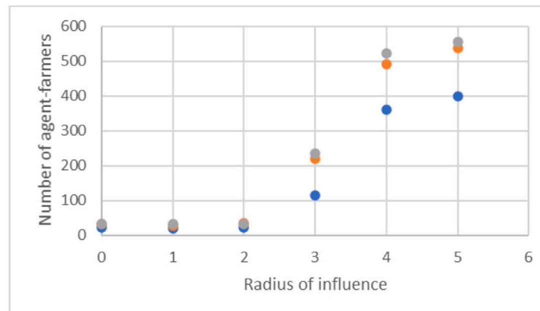


Increased awareness due to the network, *incS_N=1*

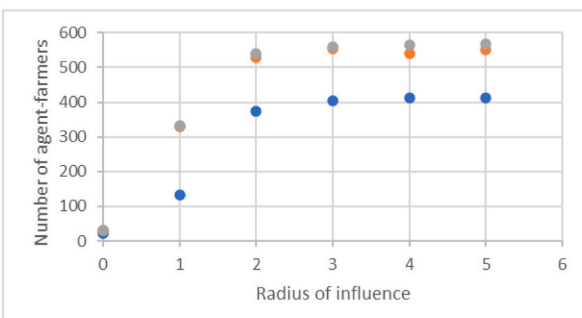
Fig. A6.1. Numbers of agent-farmers who have changed their practice, depending on the radius of influence of neighbors. Each graph corresponds to different Intensity of the increase in awareness. Blue points represent profile A. Orange point represent profile B and grey points represent profile C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



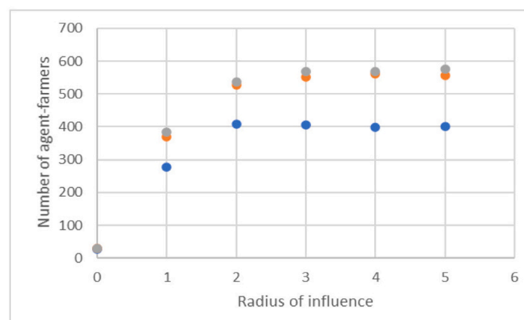
Increased knowledge due to the network, *incK_N=0*



Increased knowledge due to the network, *incK_N=0.1*



Increased knowledge due to the network, *incK_N=0.5*



Increased knowledge due to the network, *incK_N=1*

Fig. A6.2. Numbers of agent-farmers who have changed their practice, depending on the radius of influence of neighbors. Each graph corresponds to different Intensity of the increase in knowledge. Blue points represent profile A. Orange point represent profile B and grey points represent profile C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

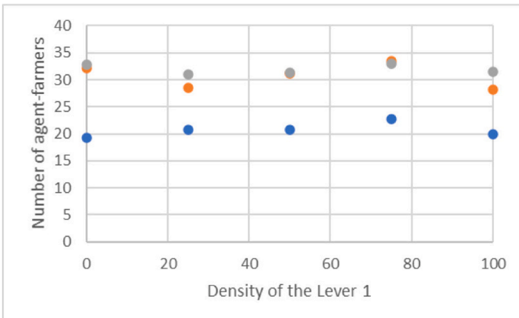
Effect of lever-related parameters

To assess the influence of the parameters associated with levers, we first neutralized the effect of the neighbors. We tested levers one by one crossing the density $radLev_{Lev,\ RLev}$ and the number of repetitions *RLev*.

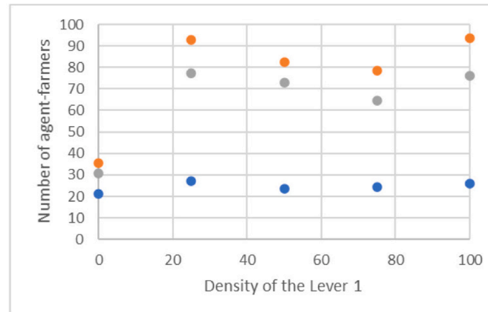
For Levier 1 and 2, a higher number of repetitions leads to more agent-farmers changing their practice. The increase is particularly strong between 0 and 25 repetitions, but beyond that point, additional repetitions yield progressively smaller gains. Moreover, the density of the lever has a clear effect only between values of 0 and 20; beyond this range, density no longer appears to influence the number of farmers adopting the practice.

However, density does influence the *spatial* pattern of adoption. As shown in Fig. A6.1 and A6.2, high-density settings lead to clusters of NI practices emerging geographically, whereas low-density settings produce a more dispersed pattern.

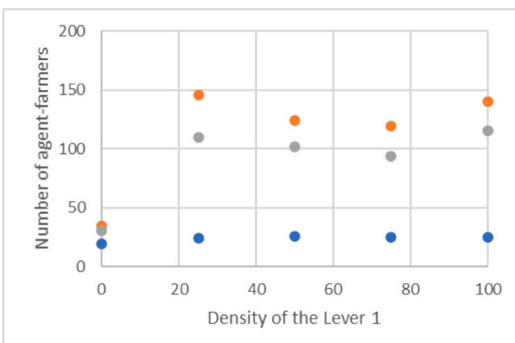
It is worth noting that Levier 2 produces stronger results, which is consistent with the fact that it reaches a larger number of farmers and generates a greater overall increase in both knowledge and awareness compared to Levier 1.



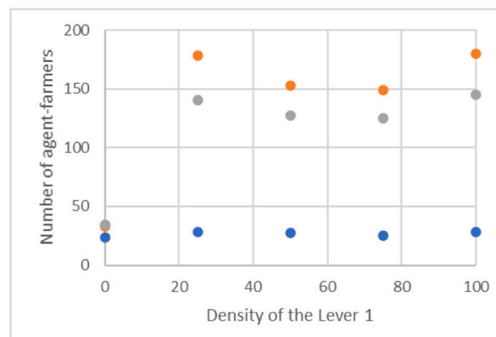
Number of levers implemented, *RLev =0*



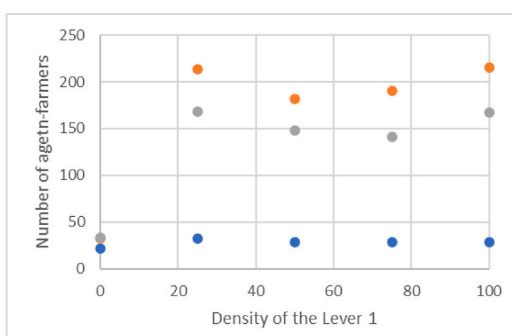
Number of levers implemented, *RLev =25*



Number of levers implemented, *RLev =50*

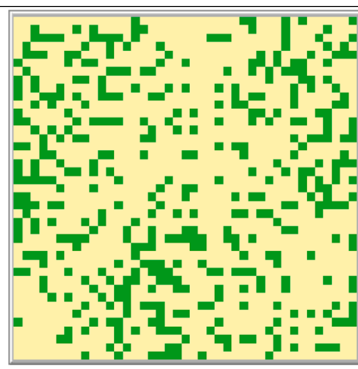


Number of levers implemented, *RLev =75*

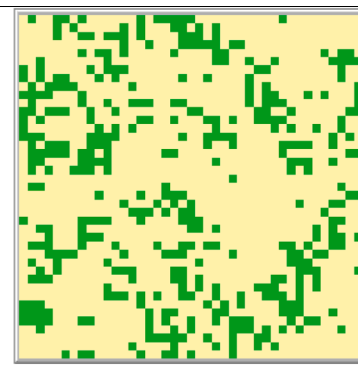


Number of levers implemented, *RLev =100*

Fig. A6.3. Numbers of agent-farmers who have changed their practice, depending on the density of the Lever 1. Each graph corresponds to different Number of levers implemented. Blue points represent profile A. Orange point represent profile B and grey points represent profile C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

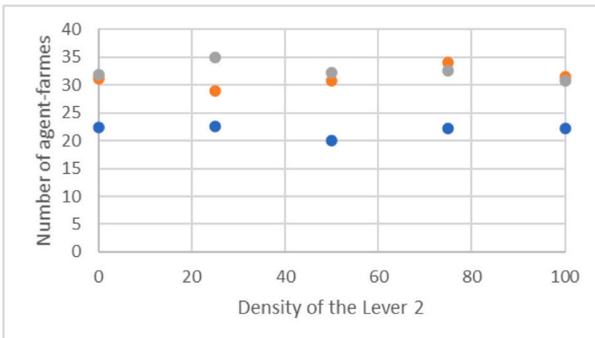


Density of Lever 1 of 20

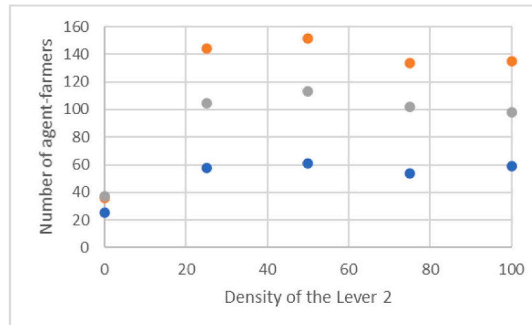


Density of Lever 1 of 100

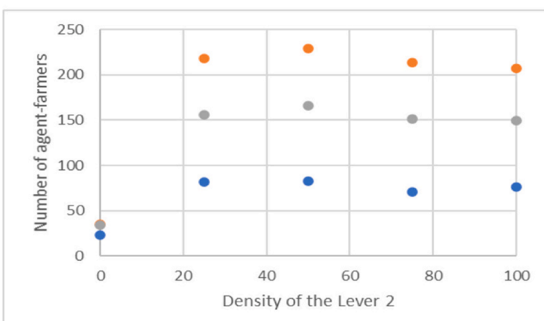
Fig. A6.4. *Images of the territory for Lever 1* with 50 repetitions of 15 agent-farmers. In yellow, HI practices and in green, NI practices. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



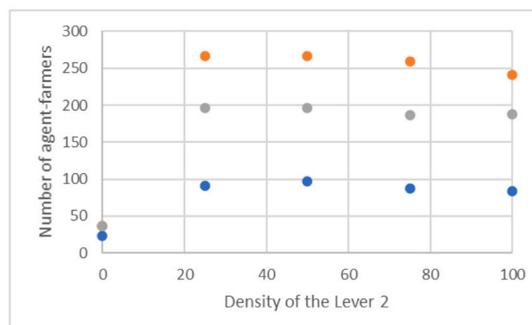
Number of levers implemented, *RLev =0*



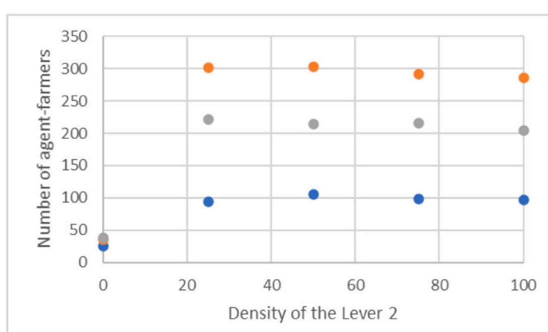
Number of levers implemented, *RLev =25*



Number of levers implemented, *RLev =50*

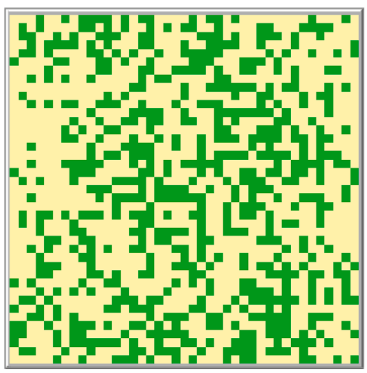


Number of levers implemented, *RLev =75*

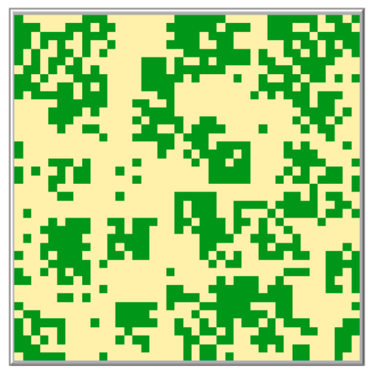


Number of levers implemented, *RLev =100*

Fig. A6.5. Numbers of agent-farmers who have changed their practice, depending on the density of the Lever 2. Each graph corresponds to different Number of levers implemented. Blue points represent profile A. Orange point represent profile B and grey points represent profile C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



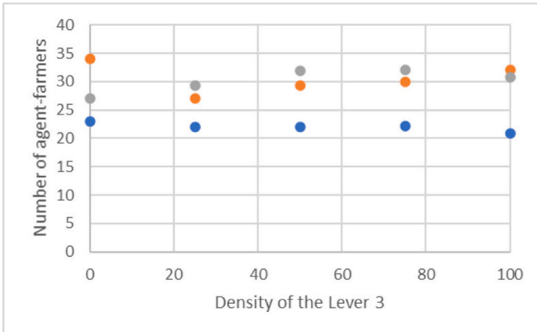
Density of Lever 2 of 20



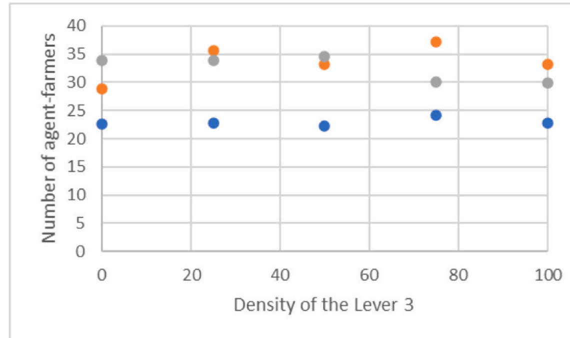
Density of Lever 2 of 100

Fig. A6.6. *Images of the territory for Lever 2* with 50 repetitions of 30 agent-farmers. In yellow, HI practices and in green, NI practices. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

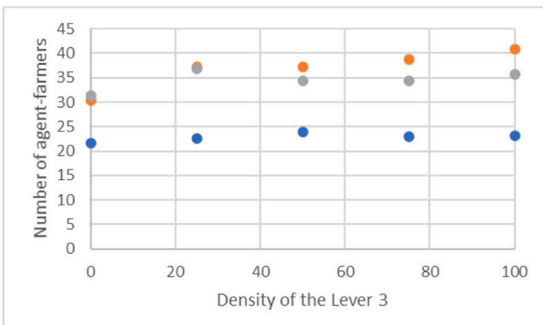
Levier 3 has only a limited effect on agent-farmers' practice change. Increasing the number of repetitions of this lever leads to only a slight increase in the number of agent-farmers adopting the practice (see Table A6.5).



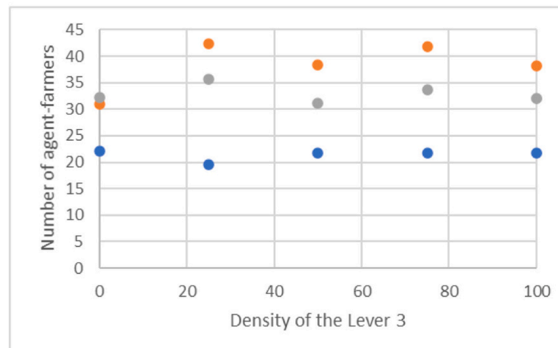
Number of levers implemented, *RLev* =*0*



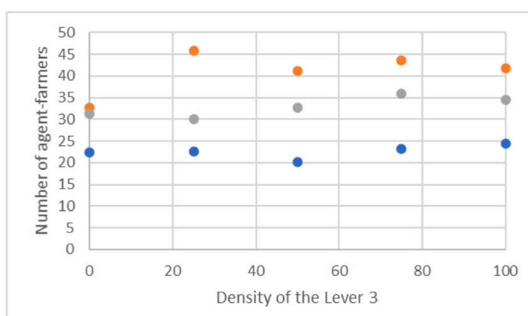
Number of levers implemented, *RLev* =*25*



Number of levers implemented, *RLev* =*50*



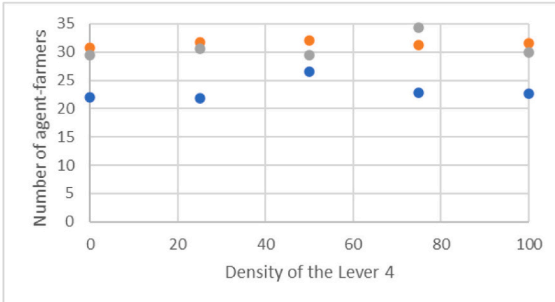
Number of levers implemented, *RLev* =*75*



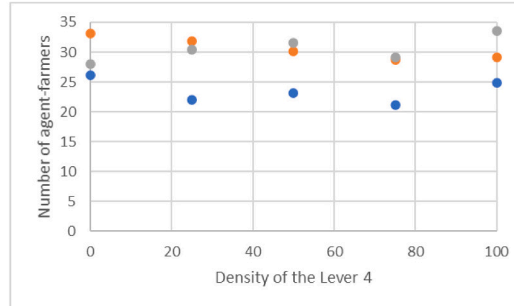
Number of levers implemented, *RLev* =*100*

Fig. A6.7. Numbers of agent-farmers who have changed their practice, depending on the density of the Lever 3. Each graph corresponds to different Number of levers implemented. Blue points represent profile A. Orange point represent profile B and grey points represent profile C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

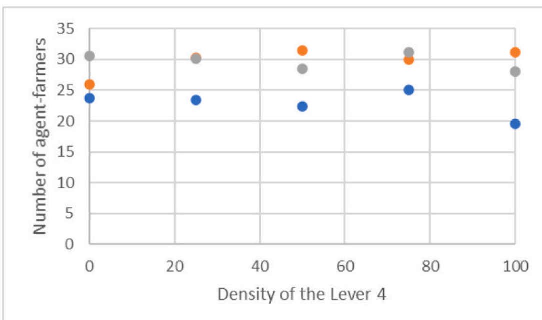
Levier 4 has no observable effect, whether we vary its density or the number of repetitions (see Table A6.6). This is due to the fact that the increases in awareness and knowledge generated by a stand at an agricultural fair are too small to influence agent-farmers' decisions. This lever would likely need to be combined with others in order to have any meaningful impact.



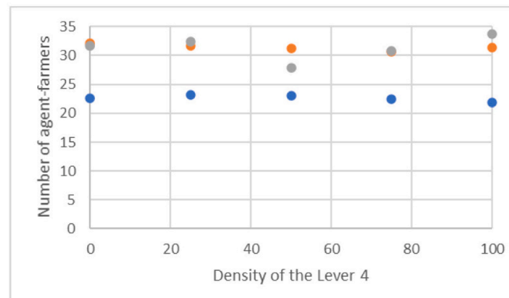
Number of levers implemented, *RLev =0*



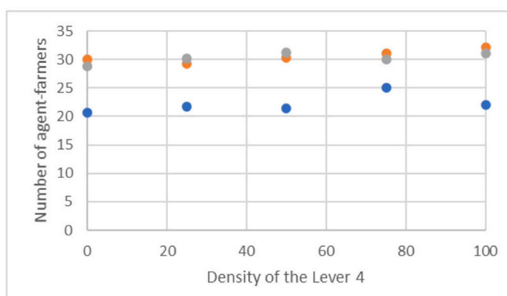
Number of levers implemented, *RLev =25*



Number of levers implemented, *RLev =50*



Number of levers implemented, *RLev =75*



Number of levers implemented, *RLev =100*

Fig. A6.8. Numbers of agent-farmers who have changed their practice, depending on the density of the Lever 4. Each graph corresponds to different Number of levers implemented. Blue points represent profile A. Orange point represent profile B and grey points represent profile C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Data availability

The model, including all code and datasets produced through the participatory process, is available on Zenodo (Bourceret, 2025).

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