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A participatory approach based on the serious game Dynamix to co-design scenarios of crop-livestock integration among farms

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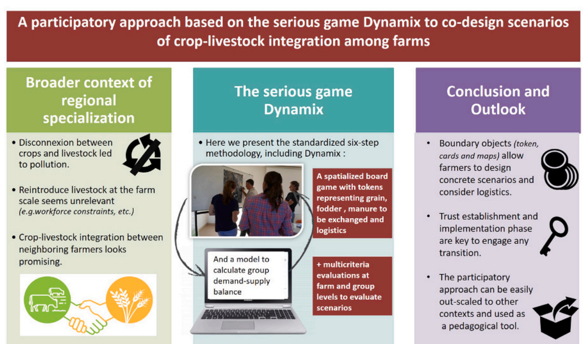
HIGHLIGHTS

- The approach co-designs crop-livestock integration among farms, as a relevant option for limiting inputs and pollution.
- The serious game Dynamix allows a spatially explicit redesign at individual farm and group level.
- Scenarios include an explicit design of the logistics of integration and multi-criteria evaluation at farm and group level.
- The scenario selected reduces logistical, legal and trust barriers involved in integration among farms.
- The serious game was applied to a case-study but can easily be scaled-out to other agricultural contexts.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Crop-livestock integration is a theoretical ideal for sustainable agriculture. However, the number of European crop-livestock farms has decreased due to multiple factors (e.g. agricultural policies and work constraints). Crop-livestock integration beyond the farm level (e.g. through grain-manure exchanges) is a relevant option to address these limiting factors. However, this integration within farmer groups is challenging because it requires collective redesign to address organizational issues.
Objective: We developed a participatory approach that includes the serious game Dynamix to support the co-design of scenarios of crop-livestock integration among farms.
Methods: The approach consists of six steps: (1) initial group meeting to define the problem; (2) farmer interviews to identify motivations and collect technical and economic farm data; (3) scenario co-design meeting using the serious game Dynamix, including a spatially explicit board game and a simulation model; (4) multicriteria evaluation of these scenarios at the individual farm and group levels using the simulation model included in Dynamix; (5) group meeting to discuss the results; and (6) monitoring of selected scenario implementation. We applied this methodology with two groups of farmers in southwestern France.
Results and conclusions: In the two groups, crop farmers wanted to diversify their cropping systems and use manure to improve soil quality. Livestock farmers were interested in local and non-GMO feed for their animals.

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The scenario they selected included i) inserting cereal-legume mixtures into crop rotations on crop farms to be sold to livestock farms and ii) transferring manure from livestock farms to crop farms. In this scenario, the predicted overall gross margin increased more for livestock farmers (median = 29.90 €/ha) than for crop farmers (median = 6.60 €/ha). Nitrogen balance management was improved: crop farmers decreased their use of mineral fertilizer by 2.8–17.4 kg/ha/year; livestock farmers decreased their feed inputs improving local feed self-sufficiency. However, farmers' workload and management complexity increased, with 22–54 h of additional work per farmer per year. Compared to other scenarios, trade-offs between individual farm and group benefits resulted in greater local autonomy in inputs but lower autonomy in decision-making. In the two groups, discussions improved trust, which is a key ingredient for transitioning to integration beyond the farm level.

Significance: Our study is the first to use a standardized participatory approach based on a serious game to support the complex issue of crop-livestock integration beyond the farm level. Applying the approach to a case-study revealed its strong potential. It can easily be scaled-out to other agricultural contexts.

1. Introduction

Farms that include crops and livestock are widely perceived as an ideal option to maintain agricultural production levels while limiting environmental impacts on soil and biodiversity (Franzluebbers et al., 2014; Hendrickson et al., 2008; Lemaire et al., 2014). However, globalized markets associated with policy incentives contributed to their decrease in number (Garrett et al., 2017), especially in Europe, due to limited availability of workforce and loss of skills (Ryschawy et al., 2013). Integration beyond the farm level could thus be a relevant alternative to address these limiting factors (Martin et al., 2016). It consists of reconnecting neighboring specialized farms through exchanges of grain, fodder, crop by-products and manure, or even by sharing land and other resources (e.g. workers, equipment).

Only a few crop-livestock integration initiatives beyond the farm level have been documented (de Wit et al., 2006; Regan et al., 2017; Ryschawy et al., 2019). Asai et al. (2018) compared worldwide case studies and identified a variety of barriers that restrict implementation of crop-livestock integration among farms. Operational barriers related to the availability of on-farm storage capacity and transportation, distance and legal aspects related to contracts and billing. Social barriers related to establishing trust and shared goals, and to the complexity of governance. Frequent meetings and communication among participants and a third party were deemed necessary to develop and maintain effective mediation (Cofré-Bravo et al., 2019). Thus, organizing highly coordinated groups of crop farmers and livestock farmers remains a challenge due to the high cost of coordination (Asai et al., 2018).

Designing and implementing crop-livestock integration among farms is a complex approach that requires addressing multiple organizational levels (e.g. field, farm, group of farms) and multiple sustainability dimensions to ensure that the benefits of the integration for certain sustainability dimensions do not come at the expense of other dimensions (Darnhofer, 2015). This integration involves systemic changes for a variety of stakeholders (e.g. farmers, advisors, supply-chain members) unified by a common intention (Pahl-Wostl and Knieper, 2014). In agreement with Darnhofer (2015), we posit that achieving such changes requires considering four main factors: beliefs and values; technologies and practices; configurations of stakeholder groups and networks; and political and macroeconomic contexts. To ensure the consistency and saliency of these designs, farmers should be the designers, and no longer considered only the beneficiaries of the solutions (Martin et al., 2013; Prost et al., 2017; Schiere et al., 2002). This objective calls for participatory approaches.

In recent decades, agronomists have increasingly used participatory approaches and, more recently, serious games to address complex problems (Souchère et al., 2010; Speelman et al., 2014). Games allow scientists, along with farmers and other stakeholders, to organize themselves to bring about an increase in the sustainability of agriculture (ComMod, 2009). By exchanging knowledge, players can design relevant future-oriented scenarios while improving their understanding of the problem, especially other players' constraints and objectives (Crookall, 2010). In particular, boundary objects such as tokens or cards promote fruitful and realistic discussions between participants and encourage a shared vision of the problems (Duru and Martin-Clouaire, 2011; Klerkx et al., 2012). Serious games can thus provide insight into scenarios that otherwise may not occur (Souchère et al., 2010).

We developed a standardized six-step participatory approach that includes the serious game Dynamix (DYNamics of MIXed systems) to support the co-design of crop-livestock integration among farms. After a general description of the participatory approach, we describe how we applied it to a case-study with two groups of farmers in southwestern France, highlighting some results. We then discuss the ability and limits of the serious game and the entire participatory approach to co-design scenarios of collaborative arrangements among farms in a local area.

2. Materials and methods

2.1. A six-step participatory method to co-design scenarios to integrate crop-livestock beyond the farm level

We adapted the method developed by Moraine et al. (2017) to co-design the crop-livestock integration scenarios. The method was based on five steps that are inspired by Börjeson et al. (2006) guidelines for designing future-oriented scenarios (Fig. 1). We added a sixth step to address the implementation of changes.

2.1.1. Step 1 – Problem definition

Step 1 consists of a group workshop to define the collective problem. The problem to be addressed can be as diverse as: which way to reduce input use locally if not possible at the farm level? how to feed animals with more local feed sources? or which crops may help diversify crop rotations while limiting inputs? etc.… The problem can be reframed to include specific local objectives (e.g. carbon-positive cropping, water-quality management, increase grassland in the area). In a session using Post-it® notes, each farmer in the group has 10 min to individually consider his/her main technical and organizational issues and expectations for crop-livestock integration within the group. A mind map is then created collectively from these notes to classify the issues and mechanisms into main categories, which are discussed for approximately 1 h to prioritize issues to consider in the participatory approach (Moraine et al., 2017).

For this first participatory meeting, a facilitator (i.e. local advisor

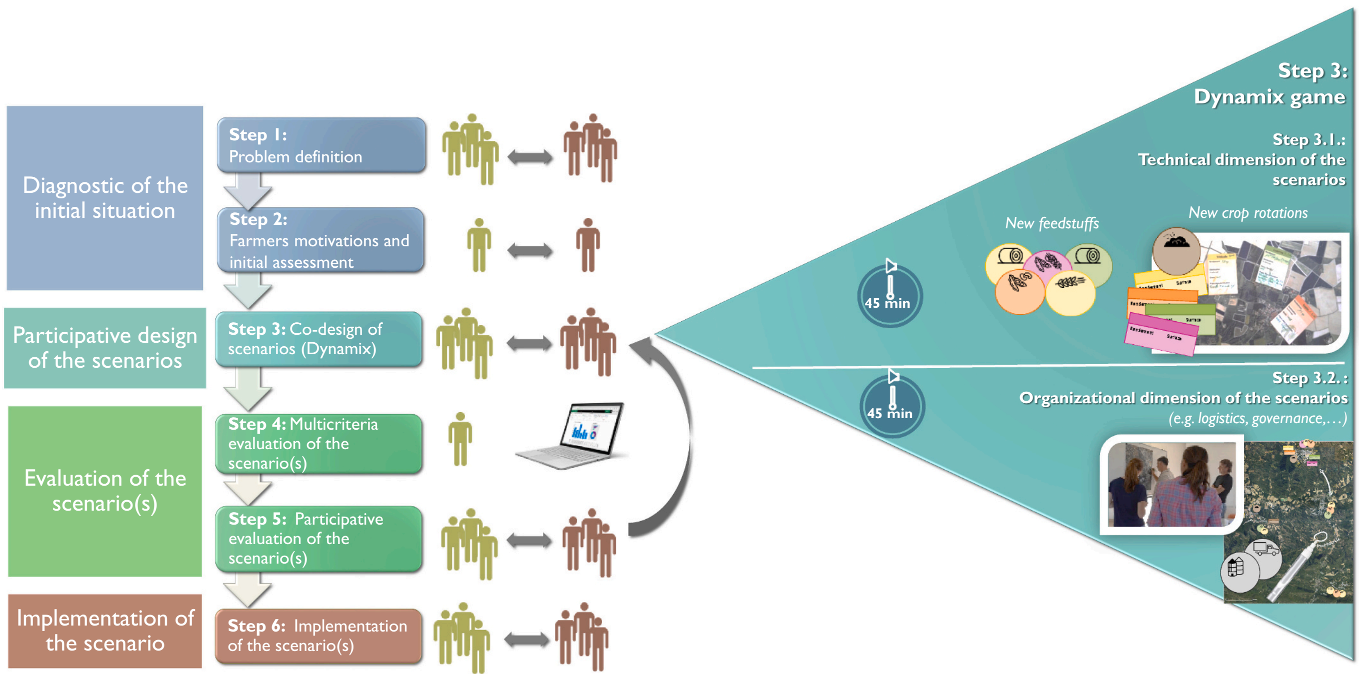

Fig. 1. The six-step participatory approach that includes the serious game Dynamix (DYNamics of MIXed systems) to co-design crop-livestock integration among farms.
Researchers are represented in green, farmers in brown

who is knowledgeable about the local area and farmers and/or a researcher involved in the process) contacts the farmers and facilitates the debate along with at least one researcher. In agreement with our previous studies on this topic (Moraine et al., 2017), we organized groups to build a polycentric governance regime (e.g. small interconnected groups of neighboring farms, as defined by Pahl-Wostl and Knieper (2014)). We considered polycentric governance as an intermediate option for in-depth farm redesign instead of fragmented governance (one-on-one exchanges), which would have precluded in-depth redesign of farms, or centralized governance (e.g. cooperative), which already exists locally and limits farmers' marketing options for crop diversification. We thus organized small groups of 10–15 farmers for the next steps, and were able to include/contact new farmers, if recommended by participants (since snowball sampling can include neighboring farmers with whom trust is already established). The distance between farmers in all groups is ideally less than 25 km, as recommended by Asai et al. (2014), to facilitate logistics.

2.1.2. Step 2 – Farmers' motivations and initial assessment

In step 2, researchers collect technical and economic data about each farm included in step 1. Based on a standardized interview guide, data are collected about farm resources (e.g. land area, soil types, animals, equipment, irrigation, workforce) and practices (e.g. grazing management, feeding management, tillage). More detailed questions about motivations are asked in an open-ended part of the interview to help researchers understand the farmer's motivations for exchanges, the products he/she would like to supply or demand and why, logistical aspects and the form of governance he/she would like the group to implement. Analysis of the interviews provide i) an initial "Scenario 0" of supply-demand for each product within the group, based on those the farmers identify as already being exchanged or sold, and ii) comprehensive analysis of farmers' motivations.

2.1.3. Step 3 – Group design of scenarios using Dynamix

Step 3 entails co-designing the scenarios using the serious game Dynamix. Dynamix helps participants design exchanges among themselves to achieve local self-sufficiency in inputs when self-sufficiency is not possible at the farm level. The technical objective of the collaborative arrangement beyond the farm level was thus to balance the supply and demand of each type of product; for instance, supply comes from grain maize in crop farmers' rotations, while demand comes from livestock farmers to feed their animals. Dynamix combines a spatially explicit board game that represents the group area and its farms combined with a model that evaluates scenarios of crop-livestock integration among farms. Farmers are first invited to redesign their farm in an individual step to include collective innovations, such as growing and selling a new crop or grassland type for crop farmers and incorporating the corresponding new feedstuffs in feeding system for livestock farmers (sub-step 3.1). Farmers then discuss logistics and group organization as a group (sub-step 3.2). A standardized game session using Dynamix lasts approximately 1.5 to 2 h, as detailed in the following sections.

2.1.3.1. Sub-step 3.1. – Technical dimension of the scenarios. In the first sub-step of the game session, farmers redesign their own farms using token and cards that represent the crops, grassland, animals and by-products (e.g. manure, straw) that they would sell or buy (Fig. 2). Crop farmers redesign their cropping system with the help of the local advisor and/or researcher, who facilitate the session and help them identify the game pieces and cards. Crop farmers receive a map of their fields that indicates current land use and are asked to suggest (new) crops or grasslands that they would produce to sell to the livestock farmers and to specify the area grown and expected yield. In return, they can expect to receive manure and are asked to quantify the amount they need. Each type of product is represented by a color so farmers can observe the increase in diversity visually: cereals in yellow, oilseed and protein crops in orange, grassland (and grass hay/silage) in green, mixed crops in rose, manure in brown and straw in light yellow.

Meanwhile, livestock farmers redesign their feeding systems using the Forage Rummy board game (Martin et al., 2011) to ensure that their self-sufficiency in feedstuffs will not decrease while sourcing more local grain and/or fodder. At this stage, livestock farmers adapt their feeding systems in accordance with other options they may select, e.g. increase or decrease their stock numbers and stocking rates, change breed, production levels and/or orientations, modify calving periods and even

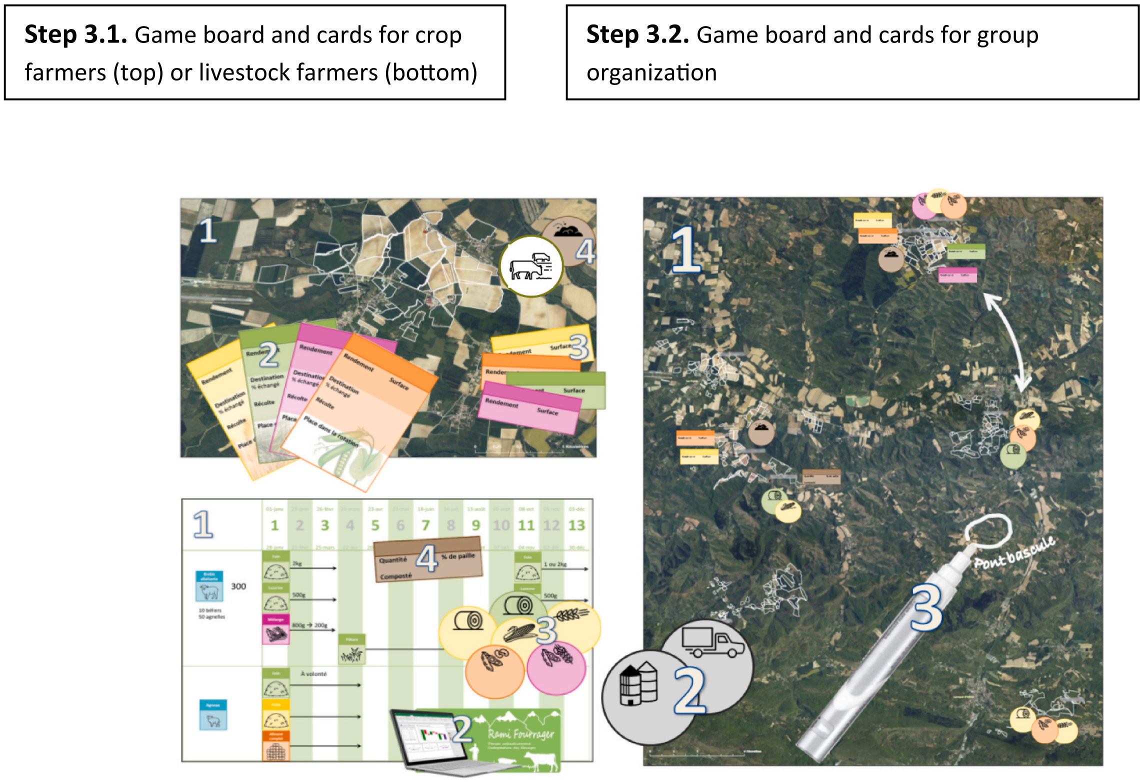

Fig. 2. Game board and boundary objects used in the serious game Dynamix.
At the top left, the individual boundary objects for crop farmers. On (1) a map of their fields and current land use, crop farmers are given (2) rectangular larger square cards to identify the crop land-use and product/by-product supply that correspond to the crops, grassland or cover crops to be inserted into their rotation to sell to the livestock farmers. They can detail all technical operations on these cards and summarize only the type of crop/grassland, expected yield, and area on (3) smaller cards, used in step 3.2. They can also use (4) a round "demand" token to request manure.On the right, the organizational dimension step, based on (1) a map of the group area that includes all of the' farms, on which farmers place the "supply" and "demand" tokens they used in the previous step near their farm headquarters and then (2) design the logistics with specific storage and transport tokens, on which they specify the type and amount of product to store/transport. At the end, farmers can use (3) a white felt-tip pen to add anything required for the next steps (e.g. new farmer, local cooperative equipment). At the bottom left, the individual boundary objects for livestock farmers: (1) Forage Rummy board and cards to detail animal types, feed requirements and feeding systems, (2) model to test the balance between on-farm crop/grassland production and animal feed requirements, (3) round tokens on which to write down their "demand" for fodder and/or grain from crop farmers and (4) organic manure supplied on rectangular brown "supply" tokens if stored or on round white animal "supply" tokens if animals are grazing on the parcel, e.g. a cover crop in accordance with the livestock farmers (and included in the fertilizer balance in the model).

offer to let some animals graze on another farm. Each farmer receives a board that represents 13 periods of four weeks (i.e. one year), on which they identify their own crops and grassland with cards marked with year-round grain or forage production and animal feeding requirements. The advisor then calculates the resulting supply-demand balances at the farm level using a computerized support system. This step lasts approximately 45 min. Crop farmers are able to discuss options to implement with livestock farmers throughout the step, since they work in the same room.

2.1.3.2. Sub-step 3.2. – Organizational dimension of the scenarios. The second sub-step of the game session starts with a roundtable during which the farmers successively place their tokens and cards on a poster (A0 size) that shows a map of the area including their farms. Farmers are invited to explain their technical proposals from sub-step 3.1. to the rest of the group (e.g. adding 3 ha of barley to sell grain to livestock farmers). Meanwhile, the facilitator fills in the group supply-demand balance table to quantify each product and help farmers adjust the exchanges and adapt their choices accordingly. Farmers are then invited to consider logistical issues concretely by considering the map and flows of products planned previously. Farmers receive storage and transport tokens on which to write the type and amount of products they can store for the group and/or specify a lack of storage facilities (Fig. 2). They consider transport issues the same way, including knowledge about local transporters or facilities, and use the map to imagine routes that improve transportation. Farmers are invited to use a white felt-tip pen to draw important organizational elements (e.g. weigh stations, possible routes) as well as to identify farmers who could join the group. This sub-step helps them organize the logistical aspects visually. Farmers then discuss the group organization they would like to adopt (e.g. pairwise exchanges for specific products/by-products, group investments to store grain), as well as barriers to and mechanisms for implementing the scenarios, along with a schedule for future work. This step lasts approximately 45 min and is followed by a more informal collective discussion and short social event, such as sharing a cup of coffee.

2.1.4. Step 4 – Multicriteria evaluation of the scenarios using the Dynamix model

In step 4, scenarios are evaluated using the Dynamix model to i) quantify supply-demand balances of the crops, fodder and manure exchanged and ii) perform multicriteria evaluation at the farm and group levels (Ryschawy et al., 2019).

2.1.4.1. Quantifying supply-demand balances. The supply-demand balance is first calculated at the farm level and then aggregated at the group level. It is detailed for crop and grassland products (i.e. to feed animals) and manure. At the farm level, we use tools developed to focus on self-sufficiency in animal feeding and manure at the crop-livestock farm level (CLIFS; (Le Gal et al., 2011; Ryschawy et al., 2014) along with Forage Rummy (Martin et al., 2011). The initial scenario (S0) is thus calculated using the farm survey data from step 2 and national databases to provide information parameters for the model.

Since individual farm and group levels are dynamically interconnected, the sum of farm-level supply and demand determines the supply and demand at the group level. To assess the supply-demand balance at the group level, we use a computer spreadsheet that summarizes the amounts of products supplied and demanded (columns) by each farmer (lines) (Appendix A).

We consider livestock and crop systems separately. For livestock systems, we focus on the feeding system and manure production. The model determines the supply-demand balance by comparing farmers' animal types and feeding systems to animal-feed requirements based on the INRA feeding tables (INRA, 2007). It estimates manure production as a function of animal type and housing (CORPEN, 2001). For cropping systems, the model considers the amount of fertilization, including available manure (if any), and pesticides used per type of crop. It then estimates yields and manure needs for inputs and crops (Terrunivia and Arvalis databases). Input costs are quantified using values from farm surveys to represent the current situation. Fig. 3 summarizes the data required as input for simulations and outputs provided by the Dynamix model.

Input data for the initial scenario (S0) come from the farm survey in step 2. To evaluate the future scenarios designed, crop and grassland yields are estimated from information provided by farmers in step 2. For crops that are not yet produced on farms, the yield is either that from neighboring farms that grow the crop or the regional reference yield from national or regional databases (e.g. national databases from the French Ministry of Agriculture; regional databases Agreste, Terrunivia and Arvalis for conventional farms or National Federation for organic farming (FNAB) and National Institute for organic farming (ITAB) for organic farms.

2.1.4.2. Multicriteria evaluation. The multicriteria evaluation grid is adapted from previous studies on farm sustainability, particularly sustainability assessment of crop-livestock systems beyond the farm level (e.g. Moraine et al., 2017; Ryschawy et al., 2019). Four key domains are considered to evaluate the scenarios: (i) efficiency of flows of products, nutrients and energy, conceptualized as the system metabolism; (ii) ecosystem services provided to agriculture; (iii) socioeconomic performances and knowledge management; and (iv) social embeddedness of farming systems. For economic, environmental and social dimensions, 24 indicators are calculated at the farm level (16, 10 and 3, respectively) and 6 are calculated at the group level (3, 1, 1 respectively and 2 regarding resilience). Appendix B details the full list of indicators available at individual farm and group levels.

Self-sufficiency in inputs and nitrogen (N) balance are calculated for all scenarios at farm and group levels. Implementation of crop-livestock integration among farms can create benefits at the group level (e.g. better N balance) and imbalances among farms (e.g. N depletion on some farms and overload on others) that are essential to capture when comparing scenarios. Moreover, a previous study highlighted that as operational costs (input costs) for crop production and animal feeding and environmental impacts decrease, workload and logistical costs for storage and transportation of products increase (Ryschawy et al., 2019). Trade-offs between individual farm and group benefits must be considered in decision-making at the group level.

At the individual farm level, trade-offs between individual dimensions of sustainability have to be considered as well as e.g. decreasing chemical inputs by including legumes in crop rotations may benefit the environmental and economic dimensions while inducing an increase in workload.

The farmers can adapt the multicriteria grid to their specific objectives and issues and thus choose and/or rank indicators from the full list. This process is known to help farmers project their ideas concretely in a near future and renders the scenarios more concrete (Lamarque et al., 2011).

2.1.5. Step 5 – Group evaluation of the scenarios

In step 5, a participatory meeting is organized with the group to discuss results of the scenario evaluation. This step includes the initial group of farmers and can also include interested new farmers mentioned during the Dynamix game session in step 3. After presenting the supply-demand balance and evaluation of each scenario designed in step 3, limits and perspectives are discussed, especially trade-offs between individual farm and group objectives and performances to identify the scenario that provides the best compromise for each farmer and the group of farmers. The scenario can be adapted at this step, and the group can decide to go back to step 3 for an iterative loop of design. The

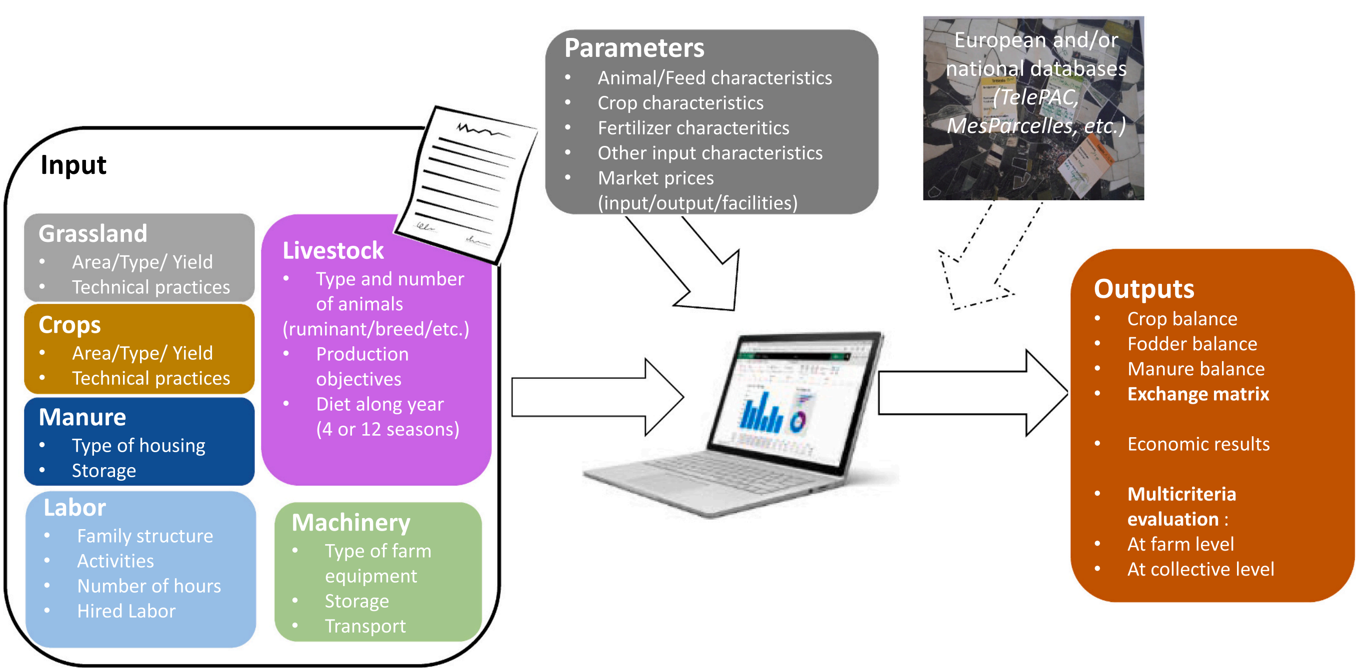

Fig. 3. Data required as input for the Dynamix model and the outputs that it provides.

meeting lasts approximately 3 h and includes refreshments to foster ties among the farmers.

2.1.6. Step 6 – Implementation of the scenario

Step 6 was added for this study, since our previous study on the topic indicated the need to continue work after implementation begins, as highlighted by Asai et al. (2018), to decrease scenario failures due to high operational costs and a lack of longer-term support. We thus continued to work with the group to help the farmers implement the changes suggested in the scenario they selected. We monitored the occurrence of expected and unexpected results through on-farm observation and discussions with farmers and their advisors. For each technical innovation (e.g. a new crop seeded, new fodder or concentrate), a dedicated local advisor visited each farmer to help him/her choose the most appropriate variety and technical management options, monitor the results and provide any technical information needed. The advisory team (i.e. facilitator or local advisor) keeps in close contact with the farmers (e.g. calling every 2–3 months to discuss needs and potential participation in group meetings organized locally with farmers and advisors).

2.2. Case-study application

2.2.1. Local area with an emerging problem

We applied the standardized participatory approach to a case-study in Ariège, a French NUTS 2 region that contains four main types of agricultural areas, based on soil and climate conditions (Fig. 4). We considered two of the types of areas:

1) valley areas, where specialized crop farmers grow maize monocultures for seed production along with wheat-sunflower rotations. These crops have high market prices, but their production practices rely on pesticides, mineral fertilizers and irrigation.
2) foothill areas, with livestock systems (i.e. beef cattle, sheep) based on a combination of crops and grassland due to conditions that are less favorable for cropping (e.g. shallow soils, slopes).

The spatial organization of the case-study area influences the logistical aspects of crop-livestock integration strongly. Only one main road connects France to Spain across Pamiers and the Pyrenees Mountains. In the foothill areas, the road network is less dense, narrower and more sinuous than that in valleys. These features often render access by large trucks difficult.

2.2.2. Emergence of the local partnership that led to the participatory approach

The participatory approach has experienced a variety of events from the creation of the farmer groups to the current implementation of changes. Since 2014, the farmer's association "Conser'sols" has facilitated interaction among 30 crop farmers in a local peer-to-peer network. With their local advisor, they worked on a local project for four years with the aim to transition toward conservation agriculture. Starting with the introduction of cover crops and diversification of their crop rotations, they searched for markets for their new crops (e.g. alfalfa) and for organic fertilizers. Their advisor discovered studies on crop-livestock integration beyond the farm level led by INRAE researchers in Toulouse (France) and contacted the researchers to initiate the participatory approach with farmers. In 2017, the advisor's local Chamber of Agriculture set up a European Union (EU) agricultural European Innovation Partnership (EIP-AGRI) Operational Group project "Rotations 4/1000" to strengthen this new collaboration. The project remains ongoing and involves the Conser'sols association, INRAE and the French institutes for cereals (Arvalis) and oilseed and protein crops (Terres Univia).

2.2.3. Applying the six-step participatory method to the case study

Implementing the participatory approach in 2017 resulted in two

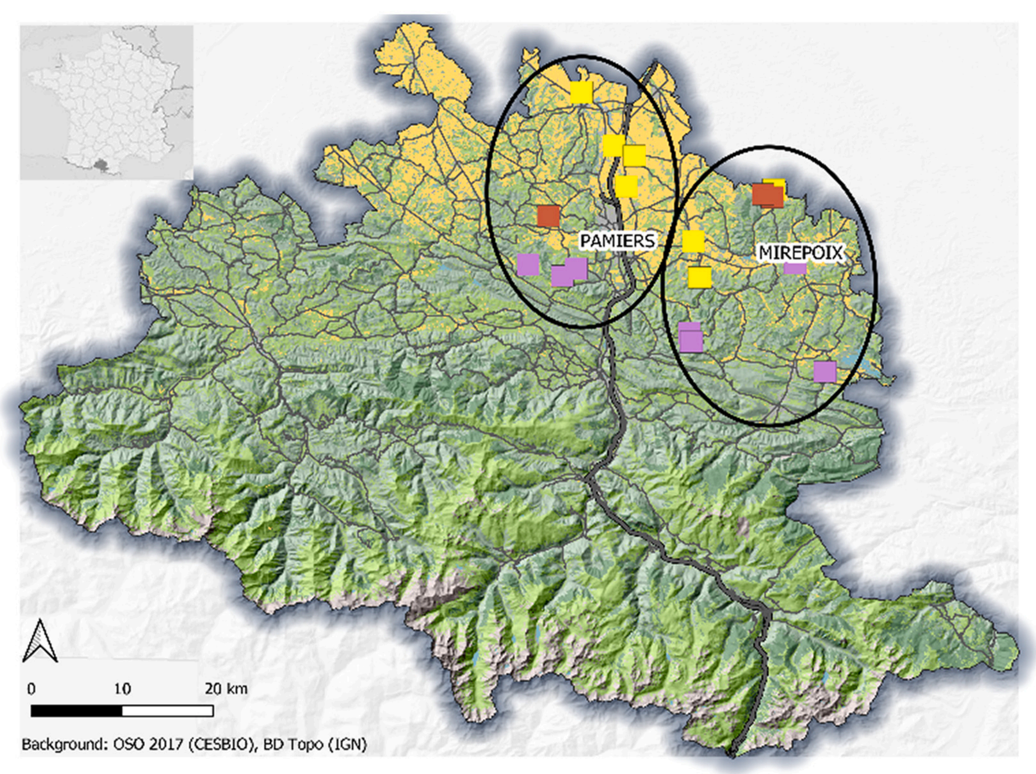

Fig. 4. Map of the case-study area showing locations of the farmers involved in the two groups of crop farmers and livestock farmers.
The colors indicate the type of farm: livestock farms (purple), crop farms (yellow) and crop-livestock farms (brown). Valley areas are located around Pamiers, while foothill areas are located around Mirepoix. No farmers in the group were located in mountain areas.

different groups of farmers gathered according to the location of their farms. The aim was to build small groups of neighboring farms as recommended by Asai et al. (2014). The Pamiers group was made of five crop farmers and three livestock farmers located in valley areas; the Mirepoix group was made of four crop farmers and five livestock farmers located in foothill areas. We first contacted the crop farmers to identify those who might be interested in participating in a group with livestock farmers. We then asked them to recommend relevant livestock farmers to contact and built the group via snowball sampling. The two groups separately experienced the 6-step participatory methodology presented in Section 2.1 . They experienced different events (some of them negative) during the multi-year participatory process (Appendix C). Table 1 details the application of the participatory approach to the case study.

3. Results

3.1. Step 1 – Problem definition

The focus group on carbon-positive crop rotations gathered farmers with a shared interest but it quickly came out that the problems to be solved for crop and livestock farmers went beyond carbon-related issues. Both wanted to find technical ways to reduce their use of inputs.

Crop farmers were concerned about their use of mineral nitrogen and pesticides. They had been involved for 4 years in a transition toward conservation agriculture and were facing two major challenges: i) a soil quality remaining too poor along with a reliance on mineral fertilizers and ii) a lack of market for the cover crops and grasslands they had started to include (or were willing to) in their crop rotations to limit pesticide use through crop diversification with e.g. mixed crops or alfalfa that livestock farmers could use to feed their animals.

Livestock farmers had a dependency to purchased feed concentrates, in particular protein-rich ones that they would buy at a high price at local suppliers. They were looking for an alternative to soybean meal to relocalize animal feedstuff. Pulses that require no processing were listed, such as pea, faba bean and lupine. Livestock farmers were highly concerned about not knowing the exact balance of pulses and cereals they should provide to the different types of animals, especially in the case of mixed crops. Their main problem was not only technical as they also mentioned they would like to regain their autonomy for decision as regards to feed industries.

Both types of farmers had no opportunity to unlock these problems at the farm level as they had already tried to improve their systems through the work done with their advisors and their local farmer associations. Crop-livestock integration among farms thus emerged as a salient options to explore together.

Table 1
Application of the six-step participatory approach to the case-study in Ariège (France).

Step	Method application	Number and types of stakeholders involved	Detailed schedule
1 –Problem definition	A focus group on carbon-positive crop rotations to allow farmers redesign crop rotations to diversify crops, include grasslands and cover soils while feeding animals. Organized during the annual general assembly of Conser'sols (2017)	- 16 crop farmers - 5 livestock farmers - 4 advisors - 2 researchers	2-h meeting with 4 sub-groups - individual Post-it® notes to list new crops/grasslands - Group design of rotations that included them - Presentations between sub-groups
2 – Farmers' motivations and initial assessment	- Volunteer crop farmers - Snowball sampling to find neighboring livestock farmers	17 individual interviews: - 9 crop farmers - 8 livestock farmers	On average, 1 h for crop farmers and 2 h for livestock farmers (with feeding systems)
3 – Group design of scenarios using Dynamix	Two groups defined to limit the distance between volunteer farmers in step 2: - Pamiers group in valley areas - Mirepoix group in foothill areas	Pamiers group: - 5 crop farmers - 3 livestock farmers Mirepoix group: - 4 crop farmers - 5 livestock farmers For each group: 2 local advisors and 2 researchers	A 2-h meeting using the board game of Dynamix for each group: - Sub-step 3.1. for the technical dimension - Sub-step 3.2. for the organizational dimension
4 – Multicriteria evaluation of the scenarios	Model used as a "back office" to evaluate the scenarios	Farmers selected only one indicator per dimension (economic, environmental and social) to obtain a rapid overview of scenarios at the farm level: overall gross margin, farm-gate nitrogen balance and workload, respectively.	- Indicators calculated by a researcher in the laboratory - Detailed minutes sent to all farmers by e-mail
5 – Group evaluation of the scenarios	Group discussion to present the multicriteria evaluation of the scenarios	Pamiers group: - 3 crop farmers - 2 livestock farmers Mirepoix group: - 3 crop farmers - 3 livestock farmers For each group: 3 local advisors (in charge of crop, livestock and organic production)	- A 3-h meeting to present and discuss the scenario evaluation - Distribution of flyers on technical, logistical and legal questions from the last meeting Refreshments at the end to foster ties among the farmers
6 – Implementation of the scenario	Collection of additional technical information and involvement of new advisors and partners. - Monitoring of on-farm implementation of the scenarios (1 or 2 farm visits, depending on the farmers' needs)	- The farmers involved in step 5, for both groups	- New rounds of interviews to follow up - Technical visits by an advisor to implement new crops and/or feeding systems

3.2. Step 2 – Farmers' motivations and initial assessment

3.2.1. Step 2.1 - Initial scenario

3.2.1.1. Farming systems in the initial scenario. Farmers in each group produced a variety of cash crops and/or animals in the initial scenario (Appendix D is detailing the sample of farmers and production types). In the Pamiers group, the five crop farmers grew 5–12 crops in their systems, but most were cereals. Some had grassland, but only one used it to feed animals, or even produced maize silage, since he was an agricultural contractor and already had experience working with livestock farmers. His business had previously helped address logistical aspects in the groups. The three livestock farmers reared beef cattle or sheep. They all produced permanent and temporary grassland, including alfalfa. They were self-sufficient in fodder, except livestock farmer L3, who purchased hay. Only L1 produced triticale and a cereal-legume mixture; L2 and L3 purchased only concentrates.

In the Mirepoix group, the four crop farmers were more diversified, growing 9–13 crops including cereals, oilseed and protein crops. Only one produced mixed crops (cereal-legume). Crop farmer C1 had a hybrid profile as a crop-livestock farmer with a self-sufficient beef and dairy cattle herd on his farm. The five livestock farmers had ruminant herds that were self-sufficient in fodder. Two of them purchased cereals and soybean meal, while the other three produced pigs or poultry indoors and conventionally, and purchased all feedstuff for them.

3.2.1.2. Group supply-demand in the initial scenario. In both groups, Scenario 0 highlighted an imbalance between farmers' supply and demand at the group level (Table 2). Livestock farmers required cereals (maize in both, and barley in the Mirepoix group only) that the crop farmers did not produce yet, but which they could produce easily. The supply of soybean meal was a problem, because even if crop farmers produced soybean, there was no way to process it locally. For grassland, the crop farmers who already had some did not have the equipment or knowledge necessary to produce hay and would need to sell it as standing forage. Livestock farmers could supply manure, but crop farmers could not use it if it was not composted. In the Mirepoix group, manure and straw were already exchanged between one crop farmer and one livestock farmer, but no feedstuffs were exchanged. In Scenario 0, crop farmers did not produce mixed crops, and livestock farmers were not interested in using them if they were not sorted.

Table 2
Supply-demand balance and type of products in Scenario 0 for both groups considered.

Group	Pamiers group		Mirepoix group	
Type of product	Supply-demand balance (in tons)	Type of product	Supply-demand balance (in tons)	Type of product
Cereals	- 60	Maize	- 8	Maize
Cereals	/	/	- 38	Barley
Oilseed and protein crops	- 3.5	Soybean (meal)	- 11.7	Soybean (meal)
Grassland	+ 122	Natural grassland (standing fodder)	+ 86	Natural grassland (standing fodder)
Grassland	+ 100	Alfalfa (standing fodder)	0	/
Total straw	+ 280	Wheat straw	- 154	All types of cereal straw
Total manure	+ 400	Ovine and bovine	+ 100	Bovine

* (+) are meant for « supply » whereas (−) are meant for « demand ».

3.2.2. Step 2.2. Analysis of farmers' motivations to join the group

The analysis of farmers' motivations highlighted three main dimensions: i) diversifying rotations with legumes and cover crops, ii) sourcing local feedstuffs and iii) rebuilding social links with neighbors. Crop farmers in both groups were involved in the transition toward conservation agriculture and mainly wished to sell crops that they already produced and/or that would be useful to introduce into their crop rotations. As farmer C2 in the Pamiers group said: *"For me, the main interest would be to be able to sow new crops that are not useful to me [in terms of being able to sell them] but would allow me to diversify my cropping system."* Crop farmers were more concerned about than interested in obtaining manure unless it was composted. They were especially concerned about the logistics of manure exchange, as farmer C2 mentioned: *"Getting access to manure sounds great to me, but we have to consider where it is spread and when. That's all"*. Moreover, they did not want to sell straw, since they preferred to leave it in their fields to improve soil organic matter, and were not convinced that manure provided a greater advantage.

Livestock farmers were interested in local and non-GMO feedstuffs for their animals, but were afraid of changing their feeding systems and especially those relying on complete feedstuffs. As a livestock farmer in the Mirepoix group said, "*With dairy cows, you cannot play around too much.*" Livestock farmers revealed different mindsets by considering that crop farmers had a short-term way of thinking. As livestock farmer L2 in the Pamiers group stated: *"Livestock farmers think in the longer term; we cannot say, 'Well, this year I won't feed my heifers, but I will do it for sure next year'. Crop farmers, they think on a yearly basis; they think short-term."*

Farmers were motivated to build relationships with their neighbors, but mainly in the Mirepoix group. In the Pamiers group, crop farmers in valley areas were more motivated by their gross margin than by social aspects. As a crop farmer in the Pamiers group explained, *"We sell to the cooperative. It's easier than coordinating ourselves with livestock farmers."* In the Mirepoix group, farmers focused on (re)building strong relationships between crop farmers and livestock farmers, who do not usually work together. As crop farmer C3 in the Mirepoix group explained about his interest in being part of a group: *"For me, it is more to provide solutions to livestock farmers, who are disappearing."*

3.3. Step 3 – Group design of scenarios using Dynamix

3.3.1. Sub-step 3.1- Technical component of the scenarios designed

The scenarios designed combined introduction of new crops and cover crops into cropping systems to sell to livestock farmers as feedstuffs for the herds along with manure and straw exchanges. Scenario 1 considered only small changes in buying and selling of currently available products and was initially tested at the farmers' request. Here, we focus on Scenario 2, in which cropping systems were designed to provide complete self-sufficiency in local feedstuff, since it was the most ambitious for both groups. In it, crop farmers produced too much, especially cereals, and more livestock farmers needed to be found (Table 3). In both alternative scenarios, livestock farmers highlighted their aversion to the risk of changing feedstuff, even when production levels could be maintained.

In the Pamiers group, crop farmers were rather interested in producing mixed crops (e.g. a pea-barley mix to harvest as grain) and new protein crops in general to diversify their rotations and limit mineral nitrogen input needs and pesticides. Still, regarding technical issues and risk aversion, they preferred to sell soybean that they already produced to livestock farmers. The livestock farmers were not interested in continuing to use soybean, since they had no way to toast or press it, and preferred pea or faba bean in their feeding system. Crop farmers were eager to maintain current levels of maize production, since they were highly skilled in producing it, rather than introducing triticale, which livestock farmers demanded more. This may explain the high supply-demand imbalance in cereals in Scenario 2 that remained despite further discussions. In addition, livestock farmers required straw, but

Table 3
Exchanges in the initial Scenario 0 and planned in Scenario 2 for each group of farmers.

Group	Pamiers		Mirepoix	
Total by-product	Exchanges in Scenario 0 (in tons)	Exchanges planned in Scenario 2 (in tons)	Exchanges in Scenario 0 (in tons)	Exchanges planned in Scenario 2 (in tons)
Cereals	0	+70.2	0	+81.4
Oilseed and protein crops	0	+23.5	0	+25.6
Mixed crops	0	+70.7	0	0
Hay	0	+200	0	+120
Straw	+130	+142.7	+120	+154
Manure	0	0	+240	+240

For both groups, only straw and manure exchanges already existed in Scenario 0. Crop farmers were producing more than needed by livestock farmers, who were already near self-sufficiency, except in protein concentrate. Crop farmers were supplying the local market with cereals, whereas livestock farmers were seeking mostly protein crops and temporary legume-based grassland to replace concentrates.

crop farmers wanted to keep it on their soils to improve the organic matter content.

In Mirepoix group, crop farmers were less open to testing new crops, but wanted to increase areas of crops that they currently produced and that could benefit livestock farmers. They did not want to introduce mixed crops and preferred to produce only pure stands of lupine or cereals. Livestock farmers were interested mainly in cereals and protein crops since they were self-sufficient in fodder and relied more on external feedstuffs for pigs, poultry or for fattening young animals. One unique characteristic of this group was that one farmer was a crop-livestock farmer. He tried to keep his cattle herd as self-sufficient as possible and was able to sell hay and protein crops to livestock farmers with the quality required to feed the animals adequately. Another crop farmer in the group was a former livestock farmer who was highly sensitive to the conditions of livestock farmers. Ultimately, the crop farmers and livestock farmers in the Mirepoix group planned many exchanges in Scenario 2.

3.3.2. Sub-step 3.2 - Organizational dimension of the scenarios designed

The organizational sub-step in the scenario in Dynamix provided logistical options based on mapping the flows between farms and storage capacities, and highlighted the need for additional stakeholders to participate in the groups (Fig. 5). Groups differed in the governance suggested. Farmers in the Pamiers group preferred either pairwise integration (fragmented governance) or exchanges managed by a third party, such as a local cooperative (centralized governance). They wanted normalized rules through contracts for products. Logistics would be managed by crop farmer C5, who had room and equipment to store and transport the crops and by-products, since he is an agricultural contractor. Another option would be to involve local cooperatives, which have weigh stations near farms and could write invoices and manage legal aspects of the flows.

The Mirepoix group agreed on polycentric governance and specified three subgroups in their group map (Fig. 5). Subgroup I consisted mainly of crop farmers who would produce and store the new crops, which would be delivered to subgroup II, which consisted of livestock farmers who were not self-sufficient in feeding. Subgroup III was intermediate between the two other subgroups and included cereal production and

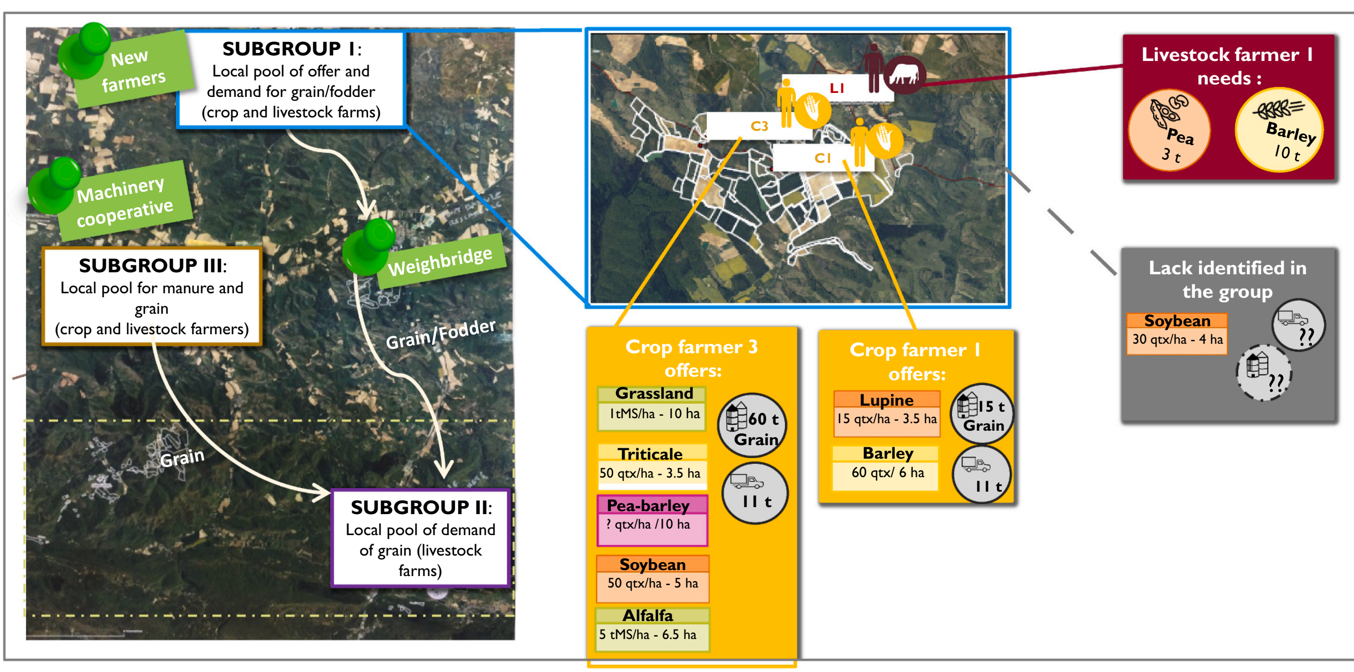

Fig. 5. Map of the group organization suggested by farmers in the Mirepoix group while playing the serious game.
On the group organization map, farmers suggested three main subgroups that highlighted the "supply" (rectangular tokens) and "demand" (round tokens) of agricultural products. Subgroup I consisted mainly of crop farmers who could produce new crops, including protein crops (lupine and soybean), harvest grassland to make hay (alfalfa and permanent grasslands) and already produced mixed crops (pea-barley) and cereals. White arrows represent flows from the new crops supplied by subgroup I to subgroup II, which consisted of livestock farmers who were not self-sufficient in feeding. The focus on subgroup I highlights i) the supply of grain and fodder (rectangular tokens) from crop farmers C1 and C3 and the logistical storage and transport options they could provide for the group, ii) the demand for grain by livestock farmer L1 (round tokens) and iii) the lack of certain protein crops and logistical options highlighted by the group that subgroup I farmers might solve. Farmers in subgroup III also planned to produce maize and wheat for livestock farmers and to exchange manure between crop farmers and livestock farmers. Green pins represent new stakeholders, and dash-dotted lines represent uncertainty in the scenarios as new stakeholders are included in the group or as farmers design new logistical tools.

straw-manure exchanges. To coordinate these subgroups, farmers considered co-creating one (or more) local platform(s) to store, weigh, evaluate quality, write invoices and transport. A platform could be created on a farm with available storage, could be purchased together or could depend on an existing organization such as a cooperative for sharing machinery. This organization would enable farmers to depend less on intermediaries, even though it would be more time-consuming at the beginning than pairwise relationships or centralized organization through an existing cooperative. Livestock farmer E2 stated: *"We must not keep the same mindset of livestock farmers versus crop farmers."*

3.4. Step 4 - Scenario simulation and multicriteria evaluation

In step 4, farmers decided to select only one indicator per dimension at the individual farm level - overall gross margin for the economic dimension, nitrogen balance for the environmental dimension and workload for the social dimension - along with a group indicator that reflected the main group objective of the scenario (e.g. improving the nitrogen balance). Farmers identified these indicators as necessary to evaluate the scenario while considering trade-offs between dimensions at the individual farm level and between individual farm and group levels.

In Scenario 2 for the Mirepoix group, the Dynamix model calculated that overall gross margin increased for all farmers, but relatively more for livestock farmers (median = 29.90 €/ha) than for crop farmers (median = 6.60 €/ha). The nitrogen balance improved, with inputs of mineral nitrogen fertilizer decreasing by 2.8–17.4 kg/ha/year on crop farms and complete nitrogen self-sufficiency on livestock farms. Scenario 2 saved 4877 kg of nitrogen per year. However, farmers' workload and management complexity increased, with 22–54 h of additional work per farmer per year. One important aspect is that some livestock farmers already worked more than 12 h per day. One livestock farmer stated, *"I have enough work for almost three people!"* These farmers either sell through direct sales or are elected members of a variety of associations or cooperatives. The trade-offs between individual and group performances seemed acceptable to the farmers and resulted in greater self-sufficiency in fertilizers and feed at the group level.

3.5. Step 5 – Group evaluation of the scenarios and perspectives

During group evaluation of the scenarios, farmers agreed with the technical aspects but highlighted the need to obtain and share new practical skills to integrate crops and livestock adequately. Farmers focused particularly on the need for technical information to explore options for species mixtures to sow, as cover crops that would be grazed efficiently or sold standing. Obtaining this information requires regular meetings and training for the entire group and technical institutes that are part of the project. Concerning legal issues, we specifically discussed the current legislation that bans selling crops directly from farmer to farmer without an official agreement, such as via a "collection and storage organization". A cooperative could weigh grain and write invoices; as one crop farmer said, *"As for exchanges, if you don't do them by the rules, one day there will be trouble."* Fodder was not considered a limiting factor, but grazing or renting of grasslands should be included in contracts.

The most important discussions addressed equity and trust. Keeping the price of each product fixed over several years would increase stability and reassurance over time and guarantee equity between crop farmers and livestock farmers. As crop farmer C3 said, *"The objective is not to make a pile of money off the backs of livestock farmers"*. The option to fix prices over several (e.g. five) years was highlighted as a relevant tool to test in the scenarios, since prices fluctuate for all farmers and stress them. As one crop farmer said, *"I can no longer handle receiving all these stressful texts from the co-op every morning saying 'Downward trend in wheat prices'!"*

3.6. Step 6 – Implementation of the scenario

Each group of farmers suggested several lock-ins and solutions during its evaluation meeting (Table 4). To address the lack of knowledge, farmers engaged in on-farm experimentation. They tested the introduction of lupine and mixed crops. The farmers were supported by the technical institutes involved in the "Rotation 4 pour 1000" project, which provided technical data. For the legal framework, local cooperatives were contacted to provide legal support for weighing crops and writing invoices. A local cooperative also offered to invest in equipment to toast protein crops. Future work is planned to provide standard contract forms, which will include price fluctuations based on climate characteristics of the given year.

For logistics and storage, one relevant option is to involve existing organizations, such as local machinery cooperatives or agricultural contractors. Since we decided to add more groups, we discussed having small groups based on a local machinery cooperative for logistical aspects, but coordinating advising, legal and prospective discussions at a

Table 4
Main lock-ins highlighted in the study and options suggested for implementing solutions.

Category	Lock-in	Solution suggested	Current status
Lack of knowledge to implement new technical practices	• Local inclusion of new crops with little experience • Livestock farmers needing to test new feeding systems	• Test new crops in rotations • Visit farms that produce new crops • Visit farms self-sufficient in feeding	• Technical assistance through the "Rotation 4 pour 1000" project • Lupine harvested in 2019 and sold to a livestock farmer • Ongoing testing of rotations on the ' farms
Logistics and storage	• Identify space for storage • Identify ways to transport the products	• On-farm storage when possible • Use intermediary agricultural contractors or cooperatives • Rely on existing machinery cooperatives	• Interviews planned with local and machinery cooperatives • Implementation of a pilot operation for manure composting and transport
Legal framework of the sales	• How to sell products legally	• Provide legal framework for all contracts • Capitalize on existing examples of farmer-to-farmer sales	• Visits with farmers or groups that legally manage storage and billing • Diffusion of examples of existing contracts for grazing or renting of grasslands
Trust and schedule	• Different timing for crop and livestock farmers • Lack of trust	• Establish a formal schedule that engages all farmers • Lead regular groups to establish trust • Maintain regular discussions about prices to ensure equity • Co-management of the groups by one crop farmer and one livestock farmer	• New groups founded for Mirepoix • One organic group labeled as a GIEE, with an advisor • One conventional group based on the GIEE"Les Steakeurs", led by farmer C1 in Mirepoix.

GIEE = "Groups of Economic and Environmental Interest", e.g. collective of farmers funded by the French Ministry of Agriculture for knowledge exchange and collective infrastructure.

larger level that included all groups. An unexpected result is that the crop-livestock farmer in the Mirepoix group became president of a local association of livestock farmers who plan to finish young cattle with only non-GMO local feed and sell their meat locally. Livestock farmers in this group are highly motivated to obtain local self-sufficiency and to work together, since they already have strong relationships. A new group thus emerged from this group of livestock farmers. The most motivated conventional crop farmers in the Pamiers and Mirepoix groups are included in this new group. A new organic subgroup was created with organic farmers from the Mirepoix group. Both groups have been certified as “Groups of Economic and Environmental Interest”, i.e. groups of farmers funded by the French Ministry of Agriculture for knowledge exchange and collective infrastructure (Lion, 2015) and planned to return to step 3.

Since then, the Mirepoix group was splet in two subgroups an organic farmer one and a conventional one. The organic farmer subgroup has enlarged including neighboring crop-livestock farmers producing high-quality alfalfa hay and a crop farmer already certified to weigh, store and sell crops what is not legal if the seller is not certified as a storage organization and/or a cooperative is involved to weigh and make invoices. The organic farmers had a meeting in July 2020 and decided with their advisor to develop a supply-demand table to be able to know who is having what products (grain, forages, …) and by-products (manure, straw, …).

The conventional subgroup engaged in a new dynamic with a group of livestock farmers selling their young cattle meat locally. These cattle farmers wanted to include local feed from Ariege in their specifications. They organized a collective meeting during July 2020 and decided that they were lacking some new actors in their group, especially to provide a local concentrate that would be already balanced for some of the livestock farmers, who did not want to make the mix themselves and did not have the material for on-farm feed production. This meeting led to the new multi-partner project FAAB (Feed production for livestock in Ariege) involving a broader set of actors: farmers, advisers, research and local cooperatives. This project is ongoing.

4. Discussion

4.1. The Dynamix serious game as a key component of the participatory approach

4.1.1. A spatially-explicit board game to co-design technical and organizational scenarios

The serious game Dynamix enabled testing scenarios of transactions between crop and livestock farmers in a participatory setting. Because crop-livestock integration among farms requires mutual agreement among farmers, the scenarios designed can appear rather conservative. The design process alternating phases of collective and individual design, it is most likely that full transformations of farm systems would not occur. Nevertheless, Dynamix reassured farmers by providing quantitative indicators about the feasibility of the scenarios and prompted them to reflect on the progressive adjustment of scenarios. Farmers expressed that it was highly useful to quantify the supply-demand balance for each type of grain or fodder exchanged. Compared to previous co-design approaches of crop-livestock exchanges between farms (Moraine et al., 2017; Ryschawy et al., 2019), the tokens and cards used in Dynamix broadened the range of testable technical innovations available to farmers, who felt comfortable with the colors and shapes used for the game pieces to describe their decisions to the other farmers. The tokens and cards represented functional entities managed by farmers, such as herds or crop fields, and were a way to facilitate conversations between farmers, as observed by Klerkx et al. (2012). The tokens, cards and group map thus operated as boundary objects, which are known to promote fruitful and realistic discussions between participants (Duru and Martin-Clouaire, 2011).

The main innovation compared to previous studies on the topic was the explicit representation of logistical needs in the board game (i.e. transportation and storage) depending on the topography, roads and location of farms on a map. Previous studies on the topic (Moraine et al., 2017: Regan et al., 2017) mentioned the logistical dimension and group organization as major lock-ins, but considered only supply-demand balances and technical aspects. In our study, the map and logistics cards promoted in-depth spatial description of logistical organization, which facilitated discussions of two governance options in the two groups. These boundary objects encouraged discussions that focused on transaction costs, such as operational costs and implementation (e.g. formal contracts, logistical planning, management needs). Asai et al. (2018) highlighted these aspects as key issues for crop-livestock integration beyond the farm level. Future steps could include quantifying costs of investing in group storage or optimizing transportation routes.

More indicators need to be developed, especially for the social dimension, to analyze in greater depth the relevance of the governance designed, in particular for the logistics of work organization and autonomy in decision-making. Regarding logistics, cooperatives could act as agents of change by managing the logistical aspects and identifying new markets (Yang et al., 2014). In our study, a machinery cooperative was suggested as a relevant option, since local peer-to-peer networks enable sharing costs and organizing logistics. This kind of network is crucial because it helps to create “bonding ties” and knowledge exchange between farmers. Networks have been highlighted as factors that help their members address logistical issues, decrease operational costs and share agroecological practices (Lucas et al., 2019). Nonetheless, economic, environmental and social costs and benefits of including a machinery cooperative in the scenarios need to be quantified for farmers to consider this option instead of other ones.

We worked closely with two groups of farmers which could be considered as two polycentric groups or “nodes”. However, we did not consider how these groups might be combined with upper-scale governing authorities levels as recommended by Biggs et al. (2012). Getting inspiration from outside agriculture would help us make process in this direction, especially in the way of including new actors such as cooperatives. Autonomy in decision being a key objective for livestock farmers in this process, the integration of new actors must be thought through and largely discuss. As highlighted by Romera et al. (2020), studies in industrial ecology have already considered the inclusion of economic firms which could help lowering input and logistical costs and should be included in a territorial network. Here, it will be relevant to consider not only the agricultural sector in a food system transition but to see how to build a coordinated network at the local level, which could articulate relationships between farmers and other actors in the territory while achieving cultural and socio-economic benefits in a so-called AES (Agroecological Symbiosis) (Koppelmäki et al., 2019). The FAAB project mentioned earlier in section 3.6. supports this perspective, as cooperatives are contributing along with other local actors.

4.1.2. A relevant decision support tool applicable to other farmer groups

Besides the board game, it is important to highlight the usefulness of the Dynamix simulation and evaluation model in the co-design approach. As Martin et al. (2016) mention, including a decision support system (DSS) that can simulate changes in scenarios instantly stimulates critical thinking and negotiations among farmers, advisors and researchers during participatory workshops.

Dynamix meets the conditions required for a DSS to be effective for design in agriculture, as Rose et al. (2016) highlight. First, DSS should be simple to use to be transferable to advisors and other case-studies. The supply-demand balance and multicriteria evaluation developed in Dynamix are based on standard technical-economic farm data used by agronomic advisors. Fewer details are required because advisors already have farm data about the feeding system, while the set of management practices, rotations and field maps are available from EU Common Agricultural Policy declarations. The parameters used to simulate the scenarios come from standardized databases and thus can be adapted easily over time. Dynamix was designed with advisors to ensure that output data required corresponds to their needs and renders the tool easily transferable. An additional step to help advisors use Dynamix will be to transfer the model to a free web platform and make it possible to update its database with online agricultural data such as those from agricultural censuses and EU's Farm Accountancy Data Network, or from databases and tools that advisors already use at the farm level. A multi-language version, including English, will be developed as well.

Second, broad use of a DSS requires that it be easy to scale out. Dynamix can be used in other contexts since its input data are easy to collect and innovations can be added. As with Forage Rummy (Martin et al., 2011) or CLIFS (Le Gal et al., 2011, 2022), which are support tools at the farm level, a new crop, grassland, cover crop or animal type can be easily added as a single line in the parameter database once references for yield are available or can be simulated. For instance, Dynamix is currently being adapted for sheep grazing in vineyards and/or cover crops owned by neighboring crop farmers. The main challenge is to obtain relevant information about such innovations. Dynamix can be used as a "toolbox" to encourage crop-livestock integration beyond farm level, since some parts can be used as an initial step for a group, even if not all farm data are available. For instance, as an initial step, farmers could use the group map to design scenarios and evaluate only the group supply-demand balance, without performing the entire multi-criteria evaluation, to obtain initial insights into options.

DSS developed by researchers often remain unused because they are not relevant to users. We developed Dynamix with end-users to ensure that the evaluation met farmer expectations. As Martin et al. (2016) mentioned, it is important for farmers to obtain multicriteria assessments of economic, environmental and social performances at the individual farm and group levels, as well as over time. Through Dynamix, farmers can choose and rank indicators from a wide range of options at both individual farm and group levels, which helps them to render the scenarios more concrete and feasible (Lamarque et al., 2011). The Dynamix model allows a large range of indicators to be calculated with minimum time and cost, as long as data are already available for each farm and group of farms. While this large range is of interest for researchers willing to explore the multiple impacts of the scenarios co-designed, integrating and interpreting these indicators and related trade-offs is a complex task. Thus, each specific group of farmers is given the opportunity to choose the specific set of indicators they would like to discuss during Step 5 to focus on the most important criteria for them, e.g. decreasing input use while not increasing workload and logistical costs too much in our groups here. By doing so, interpretation, trade-off analysis and scenario adjustment remain feasible during a workshop to verify whether the changes made in the scenarios correspond to the farmers' personal objectives, such as those regarding work organization.

4.2. The importance of the entire participatory approach for fostering integrated crop-livestock systems

A major criticism of most DSS, including serious games, is that they tend to focus on the tool to be developed rather than on its participatory use by or with stakeholders and decision makers (Barreteau et al., 2010; Basco-Carrera et al., 2017). Emphasis is often placed on the structure of the DSS rather than on how stakeholders interact with it or the specific conditions that make using it more effective (Refsgaard et al., 2005). In our case, we focused on the process to share a collective vision and solidarity to prepare for critical decisions throughout the six steps (Crookall, 2010). Below, we provide further details about the key issues identified.

First, the participatory and iterative approach enabled new stakeholders to be included after step 3, when farmers suggested them, especially to address logistical aspects (e.g. local cooperative). Allowing new stakeholders into the participatory approach is highlighted as a key factor for successful participatory approaches (Vall et al., 2016) and we ensured the inclusion of new farmers during the participatory approach, although it increased time (data collection and analyses). In our study, new farmers were included after step 3 if recommended by farmers at the end of collective step. New farmers were selected according to their production type, e.g. producing grain or fodder lacking in the collective supply-demand balance, and closeness to the group in terms of distance regarding logistics and relationships with the farmers regarding trust establishment. New farmers were directly invited in step 5 to obtain information about the scenarios evaluated and their results, to discuss technical aspects and to suggest potential next steps. At this stage, the group may decide to begin a new design loop at step 1 to redefine the problem, but they usually return to step 3 to adjust and redesign the scenarios. As Garrett et al. (2020) highlight, discussions with farmer networks are key to alter perceptions of new practices or systems, and thus to enable integrated crop-livestock systems (ICLS) to emerge in practice. Throughout the process, bonding ties among farmers emerged in both groups via group discussions and convivial moments organized during the approach, which helped to establish trust. Further study is needed to address logistical, legal and trust barriers.

Second, explicitly considering trade-offs between individual farm and group levels encouraged discussions about equity and establishing trust. This avoided a decrease in individual farm self-sufficiency in local scenarios and a loss of autonomy in decision making, unlike in other studies of crop-livestock integration beyond the farm level (Regan et al., 2017). Group discussions about establishing a price, or at least floor and ceiling prices, can increase equity in sharing the benefits of the integration planned in the scenarios. A future step could include sensitivity analysis of scenario outputs to price ranges for each product based on climate conditions and market trends. This analysis could help farmers to decide fair prices for the entire group. Equity, which lies at the heart of such group projects, can also be addressed by establishing trust (Fisher, 2013), which is promoted by using the serious game.

Finally, a major innovation of this study is related to the implementation step (step 6), in which demonstration fields (e.g. of lupine) on existing farms were a powerful tool to inspire adoption, as shown in Brazil, where ICLS were adopted more often near locations with ICLS experiments (Gil et al., 2016). The role of advisors in monitoring changes is crucial and should be followed by the researchers. One major aspect is to involve local farmers as leaders in the process to engage other farmers and encourage them to remain involved in the project. For instance, one crop-livestock farmer in the Mirepoix group became the president of a livestock farmer association, and asked the livestock farmers of this association to enter the process at step 3 and play Dynamix, which was unexpected. Although this kind of example is crucial, it cannot always be planned in advance, but could be considered throughout the entire participatory process. Unexpected results were related to implementing the process, which led step-by-step to new opportunities related to learning loops of actors involved (Argyris and Schön, 1978). During the process, we have evaluated and discussed with farmers the problems and scenarios, and allowed new farmers to enter the process to promote an open-ended process and iterative loops of co-design. In order to address potential lock-ins and allow iterative loops of design, the process thus needs to stay open-ended rather than objective-driven and thus not trying to find a one-fits-all solution.

5. Conclusion

This study was the first to use a standardized participatory approach based on a serious game to support crop-livestock integration beyond the farm level, including implementation. The case-study application showed its potential for addressing this complex issue. The method can be easily scaled-out to other contexts and is already planned to be adapted to other cases of crop-livestock integration beyond farm level, including sheep-viticulture systems in France and California, cattle grazing cover crops in Scottland and biogas production in Denmark. Further developments will be needed to include permanent crops and biogas plants in the Dynamix serious game.

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Declaration of Competing Interest

None.

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