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Julie Ryschawy, Myriam Grillot, Anaïs Charmeau, Aude Pelletier, Marc
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1 **A participatory approach based on the serious game Dynamix to co-design scenarios**
2 **of crop-livestock integration among farms**

3

4 **Ryschawy Julie¹, Grillot Myriam¹, Charmeau Anaïs¹, Pelletier Aude³, Moraine Marc²,**
5 **and Martin Guillaume¹**

6 ¹ AGIR, Université de Toulouse, INPT, INRAE, 31320 Auzeville, France

7 ² UMR 0951 INNOVATION, INRAE, CIRAD, SupAgro, 34060 Montpellier, France

8 ³ Chambre d'Agriculture de l'Ariège, 09000 Foix, France

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10 **Corresponding author:** julie.ryschawy@inrae.fr

11

12 **Highlights**

- 13 • The approach co-designs crop-livestock integration among farms, as a relevant
14 option for limiting inputs and pollution.
- 15 • The serious game Dynamix allows a spatially explicit redesign at individual farm and
16 group level.
- 17 • Scenarios include an explicit design of the logistics of integration and multicriteria
18 evaluation at farm and group level.
- 19 • The scenario selected reduces logistical, legal and trust barriers involved in
20 integration among farms.
- 21 • The participatory approach and serious game were applied to a case-study but can
22 easily be scaled-out to other agricultural contexts.

23

24

25 **Abstract**

26 CONTEXT: Crop-livestock integration is a theoretical ideal for sustainable agriculture.
27 However, the number of European crop-livestock farms has decreased due to multiple
28 factors (e.g. agricultural policies and work constraints). Crop-livestock integration beyond the
29 farm level (e.g. through grain-manure exchanges) is a relevant option to address these
30 limiting factors. However, this integration within farmer groups is challenging because it
31 requires collective redesign to address organizational issues.

32 OBJECTIVE: We developed a participatory approach that includes the serious game
33 Dynamix to support the co-design of scenarios of crop-livestock integration among farms.

34 METHODS: The approach consists of six steps: (1) initial group meeting to define the
35 problem; (2) farmer interviews to identify motivations and collect technical and economic
36 farm data; (3) scenario co-design meeting using the serious game Dynamix, a spatially
37 explicit board game; (4) multicriteria evaluation of these scenarios at the individual farm and
38 group levels using the simulation model included in Dynamix; (5) group meeting to discuss
39 the results; and (6) monitoring of selected scenario implementation. We applied this
40 methodology with two groups of farmers in southwestern France.

41 RESULTS AND CONCLUSIONS: In the two groups, crop farmers wanted to diversify their
42 cropping systems and use manure to improve soil quality. Livestock farmers were interested
43 in local and non-GMO feed for their animals. The scenario they selected included i) inserting
44 cereal-legume mixtures into crop rotations on crop farms to be sold to livestock farms and ii)
45 transferring manure from livestock farms to crop farms. In this scenario, the predicted overall
46 gross margin increased more for livestock farmers (median = 29.90 €/ha) than for crop
47 farmers (median = 6.60 €/ha). Nitrogen balance management was improved: crop farmers
48 decreased their use of mineral fertilizer by 2.8-17.4 kg/ha/year; livestock farmers decreased
49 their feed inputs improving local feed self-sufficiency. However, farmers' workload and
50 management complexity increased, with 22-54 hours of additional work per farmer per year.

51 Compared to other scenarios, trade-offs between individual farm and group benefits resulted
52 in greater autonomy in inputs but lower autonomy in decision making. In the two groups,
53 discussions improved trust, which is a key ingredient for transitioning to integration beyond
54 the farm level.

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

59

60 **Keywords:** action research, co-design, future scenarios, integrated crop-livestock systems,
61 serious game, agroecological transition

62

63 **Introduction**

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

73 Only a few crop-livestock integration initiatives beyond the farm level have been documented
74 (de Wit et al., 2006; Regan et al., 2017; Ryschawy et al., 2019). Asai et al. (2018) compared
75 worldwide case studies and identified a variety of barriers that restrict implementation of

76 crop-livestock integration among farms. Operational barriers related to the availability of on-
77 farm storage capacity and transportation, distance and legal aspects related to contracts and
78 billing. Social barriers related to establishing trust and shared goals, and to the complexity of
79 governance. Frequent meetings and communication among participants and a third party
80 were deemed necessary to develop and maintain effective mediation (Cofré-Bravo et al.,
81 2019). Thus, organizing highly coordinated groups of crop farmers and livestock farmers
82 remains a challenge due to the high cost of coordination (Asai et al., 2018).

83 Designing and implementing crop-livestock integration among farms is a complex approach
84 that requires addressing multiple organizational levels (e.g. field, farm, group of farms) and
85 multiple sustainability dimensions to ensure that the benefits of the integration for certain
86 sustainability dimensions do not come at the expense of other dimensions (Darnhofer, 2015).
87 This integration involves systemic changes for a variety of stakeholders (e.g. farmers,
88 advisors, supply-chain members) unified by the common intention (Pahl-Wostl and Knieper,
89 2014). In agreement with Darnhofer (2015), we posit that achieving such changes requires
90 considering four main factors: beliefs and values; technologies and practices; configurations
91 of stakeholder groups and networks; and political and macroeconomic contexts. To ensure
92 the consistency and saliency of these designs, farmers should be the designers, and no
93 longer considered only the beneficiaries of the solutions (Martin et al., 2013; Prost et al.,
94 2017; Schiere et al., 2002). This objective calls for participatory approaches.

95 In recent decades, agronomists have increasingly used participatory approaches and, more
96 recently, serious games to address complex problems (Souchère et al., 2010; Speelman et
97 al., 2014). Games allow scientists, along with farmers and other stakeholders, to organize
98 themselves to bring about an increase in the sustainability of agriculture (ComMod, 2009). By
99 exchanging knowledge, players can design relevant future-oriented scenarios while
100 improving their understanding of the problem, especially other players' constraints and
101 objectives (Crookall, 2010). In particular, boundary objects such as tokens or cards promote
102 fruitful and realistic discussions between participants and encourage a shared vision of the

103 problems (Duru and Martin-Clouaire, 2011; Klerkx et al., 2012). Serious games can thus
104 provide insight into scenarios that otherwise may not occur (Souchère et al., 2010).

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

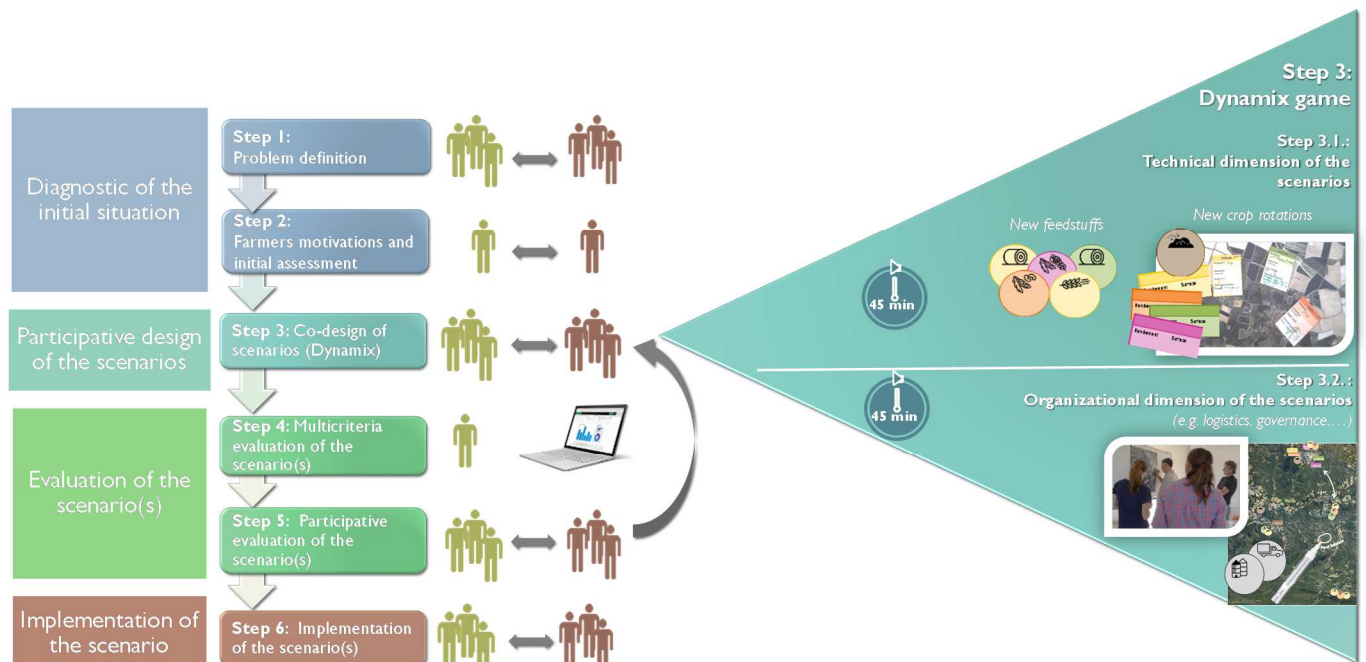
112

113 **2 – Materials and methods**

114 **2.1. A six-step participatory method to co-design scenarios to integrate crop-livestock** 115 **beyond the farm level**

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

120



121 **Figure 1.** The six-step participatory approach that includes the serious game Dynamix (DYNAMics of
 122 MIXed systems) to co-design crop-livestock integration among farms.
 123

124 *Researchers are represented in green, farmers in brown (2-column-fitting image)*

125

126 **2.1. Step 1 – Problem definition**

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

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

152

153 ***2.2.2. Step 2 – Farmers' motivations and initial assessment***

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

164

165 **2.2.3. Step 3 – Group design of scenarios using Dynamix**

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

180

181 **a- Sub-step 3.1. – Technical dimension of the scenarios**

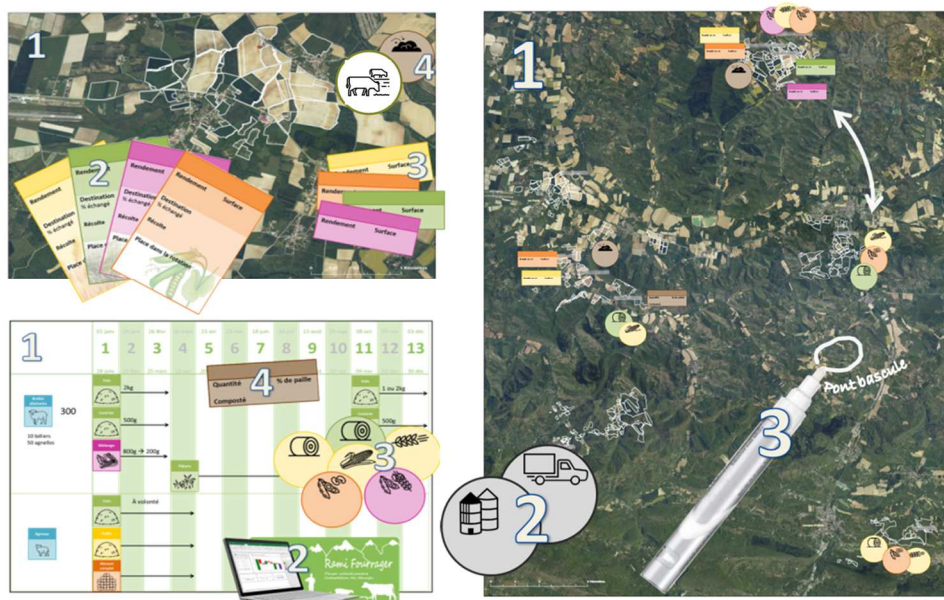
182 In the first sub-step of the game session, farmers redesign their own farms using token and
183 cards that represent the crops, grassland, animals and by-products (e.g. manure, straw) that
184 they would sell or buy (Figure 2). Crop farmers redesign their cropping system with the help
185 of the local advisor and/or researcher, who facilitate the session and help them identify the
186 game pieces and cards. Crop farmers receive a map of their fields that indicates current land
187 use and are asked to suggest (new) crops or grasslands that they would produce to sell to
188 the livestock farmers and to specify the area grown and expected yield. In return, they can
189 expect to receive manure and are asked to quantify the amount they need. Each type of

190 product is represented by a color so farmers can observe the increase in diversity visually:
191 cereals in yellow, oilseed and protein crops in orange, grassland (and grass hay/silage) in
192 green, mixed crops in rose, manure in brown and straw in light yellow.

193 Meanwhile, livestock farmers redesign their feeding systems using the board game Forage
194 Rummy (Martin et al., 2011) to ensure that their self-sufficiency in feedstuffs will not
195 decrease while sourcing more local grain and/or fodder. At this stage, livestock farmers
196 adapt their feeding systems in accordance with other options they may select, e.g. increase
197 or decrease their stock numbers and stocking rates, change breed, production levels and/or
198 orientations, modify calving periods and even offer to let some animals graze on another
199 farm. Each farmer receives a board that represents 13 periods of four weeks (i.e. one year),
200 on which they identify their own crops and grasslands with sticks marked with year-round
201 grain or forage production and animal feeding requirements. The advisor then calculates the
202 resulting supply-demand balances at the farm level using a computerized support system.
203 This step lasts approximately 45 minutes. Crop farmers are able to discuss options to
204 implement with livestock farmers throughout the step, since they work in the same room.

Step 3.1. Game board and cards for crop farmers (top) or livestock farmers (bottom)

Step 3.2. Game board and cards for group organization



205

206 **Figure 2.** Game board and boundary objects used in the serious game Dynamix

207 At the top left, the individual boundary objects for crop farmers. On (1) a map of their fields and current
208 land use, crop farmers are given (2) rectangular larger square cards to identify the crop land-use and
209 product/by-product supply that correspond to the crops, grasslands or cover crops to be inserted into
210 their rotation to sell to the livestock farmers. They can detail all technical operations on these cards
211 and summarize only the type of crop/grassland, expected yield, and area on (3) smaller cards, used in
212 step 3.2. They can also use (4) a round “demand” token to request manure. At the bottom left, the
213 individual boundary objects for livestock farmers: (1) Forage Rummy board and cards to detail animal
214 types, feed requirements and feeding systems, (2) model to test the balance between on-farm
215 crop/grassland production and animal feed requirements, (3) round tokens on which to write down
216 their “demand” for fodder and/or grain from crop farmers and (4) organic manure supplied on round
217 brown “supply” tokens if stored or on round white animal “supply” tokens if animals are grazing on the
218 parcel, e.g. a cover crop in accordance with the livestock farmers (and included in the fertilizer balance
219 in the model). On the right, the organizational dimension step, based on (1) a map of the group area
220 that includes all of the farmers’ farms, on which farmers place the “supply” and “demand” tokens they
221 used in the previous step near their farm headquarters and then (2) design the logistics with specific

222 *storage and transport tokens, on which they specify the type and amount of product to store/transport.*
223 *At the end, farmers can use (3) a white felt-tip pen to add anything required for the next steps (e.g.*
224 *new farmer, local cooperative equipment).*

225

226 ***b- Sub-step 3.2. – Organizational dimension of the scenarios***

227 The second sub-step of the game session starts with a roundtable during which the farmers
228 successively place their tokens and cards on a poster (size A0) that shows a map of the
229 area. Farmers are invited to explain their technical proposals from sub-step 3.1. to the rest of
230 the group (e.g. adding 3 ha of barley to sell grain to livestock farmers). Meanwhile, the
231 facilitator fills in the group supply-demand balance table to quantify each product and help
232 farmers adjust the exchanges and adapt their choices accordingly. Farmers are then invited
233 to consider logistical issues concretely by considering the map and flows of products planned
234 previously. Farmers receive storage and transport tokens on which to write the type and
235 amount of products they can store for the group and/or specify a lack of storage facilities
236 (Figure 2). They consider transport issues the same way, including knowledge about local
237 transporters or facilities, and use the map to imagine routes that improve transportation.
238 Farmers are invited to use a white felt-tip pen to draw important organizational elements (e.g.
239 weigh stations, possible routes) as well as to identify farmers who could join the group. This
240 sub-step helps them organize the logistical aspects visually. Farmers then discuss the group
241 organization they would like to adopt (e.g. pairwise exchanges for specific products/by-
242 products, group investments to store grain), as well as barriers to and mechanisms for
243 implementing the scenarios, along with a schedule for future work. This step lasts
244 approximately 45 minutes.

245

246 **2.2.4. Step 4 – Multicriteria evaluation of the scenarios using the Dynamix model**

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

250

251 **Quantifying supply-demand balances**

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

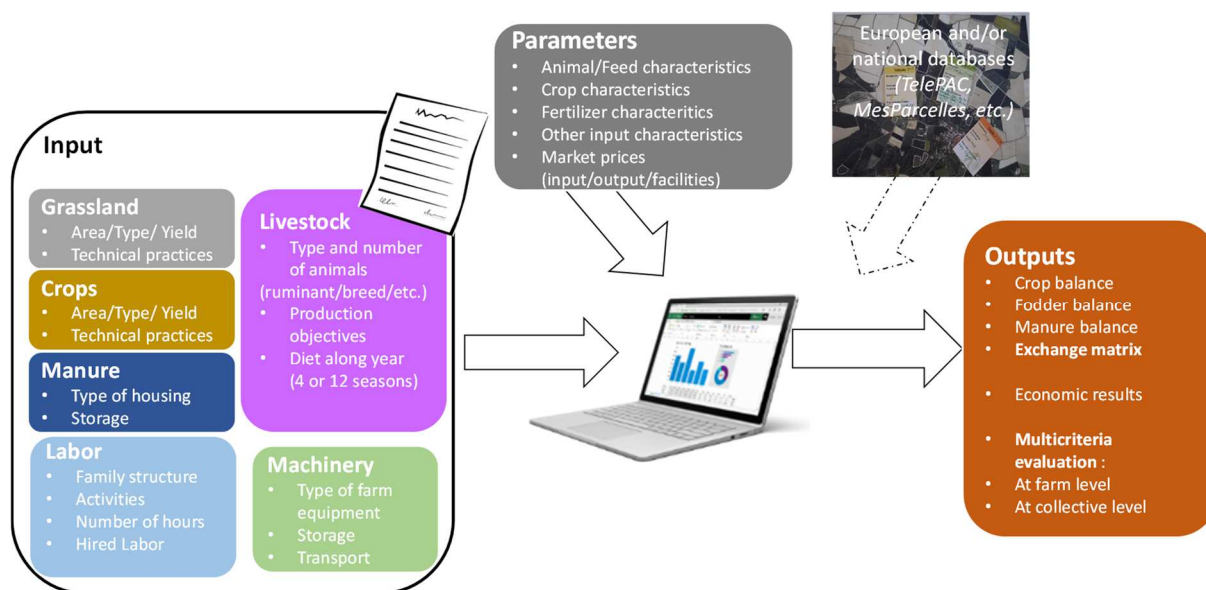
259 Since individual farm and group levels are dynamically interconnected, the sum of farm-level
260 supply and demand determines the supply and demand at the group level. To assess the
261 supply-demand balance at the group level, we use a computer spreadsheet that summarizes
262 the amounts of products supplied and demanded (columns) by each farmer (lines)
263 (Supplementary material 1).

264

265 We consider livestock and crop systems separately. For livestock systems, we focus on the
266 feeding system and manure production. The model determines the supply-demand balance
267 by comparing farmers' animal types and feeding systems to animal-feed requirements based
268 on the INRA feeding tables (INRA, 2007). It estimates manure production as a function of
269 animal type and housing (CORPEN, 2001). For cropping systems, the model considers the
270 amount of fertilization, including available manure (if any), and pesticides used per type of

271 crop. It then estimates yields and manure needs for inputs and crops (Terrunivia and Arvalis
 272 databases). Input costs are quantified using values from farm surveys to represent the
 273 current situation. Figure 3 summarizes the data required as input for simulations and outputs
 274 provided by the Dynamix model.

275



276

277 **Figure 3.** Data required as input for the Dynamix model and the outputs that it provides.

278

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

287

288 **Multicriteria evaluation**

289 The multicriteria evaluation grid is adapted from previous studies on farm sustainability,
290 particularly sustainability assessment of crop-livestock systems beyond the farm level (e.g.
291 Moraine et al., 2017; Ryschawy et al., 2019). Four key domains are considered to evaluate
292 the scenarios: (i) efficiency of flows of products, nutrients and energy, conceptualized as the
293 system metabolism; (ii) ecosystem services provided to agriculture; (iii) socioeconomic
294 performances and knowledge management; and (iv) social embeddedness of farming
295 systems. For economic, environmental and social dimensions, 24 indicators are calculated at
296 the farm level (11, 10 and 3, respectively) and 6 are calculated at the group level (3, 1, 2
297 respectively). Supplementary material 2 detail the full list of indicators available at individual
298 farm and group levels.

299 Self-sufficiency in inputs and nitrogen (N) balance are calculated for all scenarios at farm and
300 collective levels. Implementation of crop-livestock integration among farms can create
301 benefits at the group level (e.g. better N balance) and imbalances among farms (e.g. N
302 depletion on some farms and overload on others) that are essential to capture when
303 comparing scenarios. Moreover, a previous study highlighted that as operational costs (input
304 costs) for crop production and animal feeding and environmental impacts decrease, workload
305 and logistical costs for storage and transportation of products increase (Ryschawy et al.,
306 2019). Trade-offs between individual farm and group benefits must be considered in decision
307 making at the group level.

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

312 The farmers can adapt the multicriteria grid to their specific objectives and issues and thus
313 choose and/or rank indicators from the full list. This process is known to help farmers project

314 their ideas concretely in a near future and renders the scenarios more concrete (Lamarque et
315 al., 2011).

316

317 ***2.2.5. Step 5 – Group evaluation of the scenarios***

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

328

329 ***2.2.6. Step 6 – Implementation of the scenario***

330 Step 6 was added for this study, since our previous study on the topic indicated the need to
331 continue work after implementation begins, as highlighted by Asai et al., (2018), to decrease
332 scenario failures due to high operational costs and a lack of longer-term support. We thus
333 continued to work with the group to help the farmers implement the changes suggested in
334 the scenario they selected. We monitored the occurrence of expected and unexpected
335 results through on-farm observation and discussions with farmers and their advisors. For
336 each technical innovation (e.g. a new crop seeded, new fodder or concentrate), a dedicated
337 local advisor visited each farmer to help him/her choose the most appropriate variety and
338 technical management options, monitor the results and provide any technical information

339 needed. The advisory team (i.e. facilitator or local advisor) keeps in close contact with the
340 farmers (e.g. calling every 2-3 months to discuss needs and potential participation in group
341 meetings organized locally with farmers and advisors).

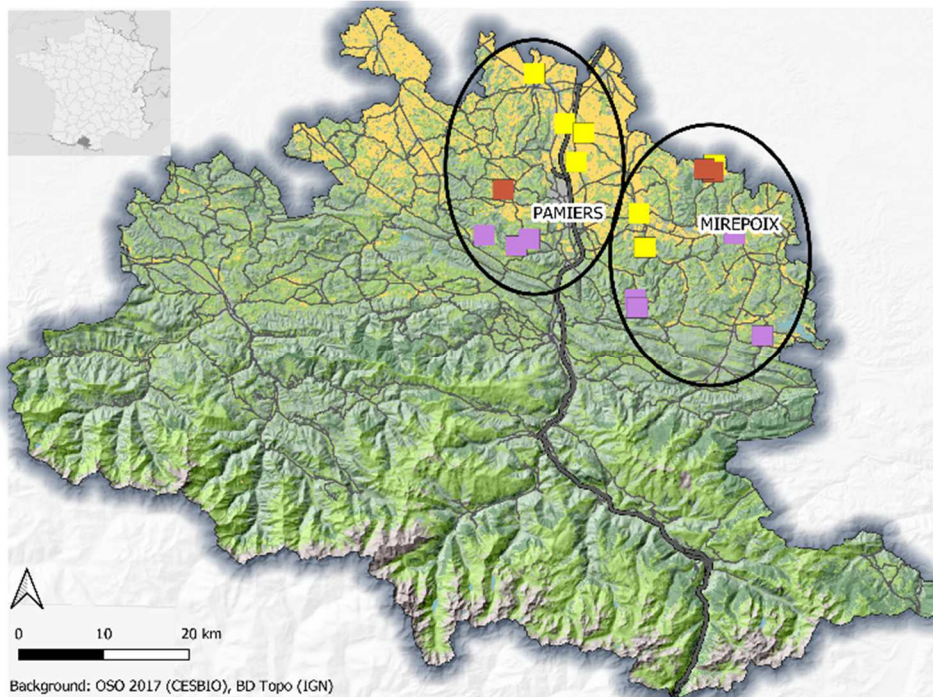
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343 **2.2. Case-study application**

344 ***2.2.1. Local area with an emerging problem***

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

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



355

356 **Figure 4.** Map of the case-study area showing locations of the farmers involved in the two groups of
 357 crop farmers and livestock farmers.

358 The colors indicate the type of farm: livestock farms (purple), crop farms (yellow) and crop-livestock
 359 farms (brown). Valley areas are located around Pamiers, while foothill areas are located around
 360 Mirepoix. No farmers in the group were located in mountain areas. (single-column-fitting image)

361

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

367

368 **2.2.2. Emergence of the local partnership that led to the participatory approach**

369 The participatory approach has experienced a variety of events from the creation of the
 370 farmer groups to the current implementation of changes. Since 2014, the farmer's

371 association “Conser’sols” has facilitated interaction among 30 crop farmers in a local peer-to-
372 peer network. With their local advisor, they worked on a local project for four years with the
373 aim to transition toward conservation agriculture. Starting with the introduction of cover crops
374 and diversification of their crop rotations, they searched for markets for their new crops (e.g.
375 alfalfa) and for organic fertilizers. Their advisor discovered studies on crop-livestock
376 integration beyond the farm level led by INRAE researchers in Toulouse (France) and
377 contacted the researchers to initiate the participatory approach with farmers. In 2017, the
378 advisor’s local Chamber of Agriculture set up a European Union (EU) agricultural European
379 Innovation Partnership (EIP-AGRI) Operational Group project “Rotations 4/1000” to
380 strengthen this new collaboration. The project remains ongoing and involves the Conser’sols
381 association, INRAE and the French institutes for cereals (Arvalis) and oilseed and protein
382 crops (Terres Univia).

383 ***2.2.3. Applying the six-step participatory method to the case study***

384 Implementing the participatory approach in 2017 resulted in two different groups of farmers
385 gathered according to the location of their farms. The aim was to build small groups of
386 neighbouring farms as recommended by Asai et al. (2014). The Pamiers group was made of
387 five crop farmers and three livestock farmers located in valley areas ; the Mirepoix group was
388 made of four crop farmers and five livestock farmers located in foothill areas). We first
389 contacted the crop farmers to identify those who might be interested in participating in a
390 group with livestock farmers. We then asked them to recommend relevant livestock farmers
391 to contact and built the group via snowball sampling. The two groups separately experienced
392 the 6-step participatory methodology presented in Section 2.1 . They experienced different
393 events (some of them negative) during the multi-year participatory process (Supplementary
394 material 3). Table 1 details the application of the participatory approach to the case study.

395

396 ***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	<p>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.</p> <p>Organized during the annual general assembly of Conser'sols (2017)</p>	<ul style="list-style-type: none"> - 16 crop farmers - 5 livestock farmers - 4 advisors - 2 researchers 	<p>2-hour meeting with 4 sub-groups</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - Volunteer crop farmers - Snowball sampling to find neighboring livestock farmers 	<p>17 individual interviews:</p> <ul style="list-style-type: none"> - 9 crop farmers - 8 livestock farmers 	<p>On average, 1 hour for crop farmers and 2 hours for livestock farmers (with feeding systems)</p>
3 – Group design of scenarios using Dynamix	<p>Two groups defined to limit the distance between volunteer farmers in step 2:</p> <ul style="list-style-type: none"> - Pamiers group in valley areas - Mirepoix group in foothill areas 	<p>Pamiers group:</p> <ul style="list-style-type: none"> - 5 crop farmers - 3 livestock farmers <p>Mirepoix group:</p> <ul style="list-style-type: none"> - 4 crop farmers - 5 livestock farmers <p>For each group: 2 local advisors and 2 researchers</p>	<p>A 2-hour meeting using the board game of Dynamix for each group:</p> <ul style="list-style-type: none"> - Sub-step 3.1. for the technical dimension - Sub-step 3.2. for the organizational dimension

<p>4 – Multicriteria evaluation of the scenarios</p>	<p>Model used as a “back office” to evaluate the scenarios</p>	<p>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.</p>	<p>- Indicators calculated by a researcher in the laboratory - Detailed minutes sent to all farmers by e-mail</p>
<p>5 – Group evaluation of the scenarios</p>	<p>Group discussion to present the multicriteria evaluation of the scenarios</p>	<p>Pamiers group:</p> <ul style="list-style-type: none"> - 3 crop farmers - 2 livestock farmers <p>Mirepoix group:</p> <ul style="list-style-type: none"> - 3 crop farmers - 3 livestock farmers <p>For each group: 3 local advisors (in charge of crop, livestock and organic production)</p>	<p>- A 3-hour 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 -</p>
<p>6 – Implementation of the scenario</p>	<p>Collection of additional technical information and involvement of new advisors and partners.</p> <ul style="list-style-type: none"> - Monitoring of on-farm implementation of the scenarios (1 or 2 farm visits, depending on the farmers’ needs) 	<ul style="list-style-type: none"> - The farmers involved in step 5, for both groups 	<ul style="list-style-type: none"> - New rounds of interviews to follow up - Technical visits by an advisor to implement new crops and/or feeding systems

398 **3 – Results**

399 **3.1. Step 1 – Problem definition**

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

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

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

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

423 **3.2. Step 2 – Farmers’ motivations and initial assessment**

424 **3.2.1. Step 2.1. Initial scenario**

425 **Farming systems in the initial scenario**

426 Farmers in each group produced a variety of cash crops and/or animals in the initial scenario
427 (Supplementary material 4 is detailing the sample of farmers and production types). In the
428 Pamiers group, the five crop farmers grew 5-12 crops in their systems, but most were
429 cereals. Some had grassland, but only one used it to feed animals, or even produced maize
430 silage, since he was an agricultural contractor and already had experience working with
431 livestock farmers. His business had previously helped address logistical aspects in the
432 groups. The three livestock farmers reared beef cattle or sheep. They all produced
433 permanent and temporary grasslands, including alfalfa. They were self-sufficient in fodder,
434 except livestock farmer L3, who purchased hay. Only L1 produced triticale and a cereal-
435 legume mixture; L2 and L3 purchased only concentrates.

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

443

444 **Group supply-demand in the initial scenario**

445 In both groups, Scenario 0 highlighted an imbalance between farmers’ supply and demand at
446 the group level (table 2). Livestock farmers required cereals (maize in both, and barley in the
447 Mirepoix group only) that the crop farmers did not produce yet, but which they could produce

448 easily. The supply of soybean meal was a problem, because even if crop farmers produced
 449 soybean, there was no way to process it locally. For grassland, the crop farmers who already
 450 had it did not have the equipment or knowledge necessary to produce hay and would need to
 451 sell it as standing forage. Livestock farmers could supply manure, but crop farmers could not
 452 use it if it was not composted. In the Mirepoix group, manure and straw were already
 453 exchanged between one crop farmer and one livestock farmer, but no feedstuffs were
 454 exchanged. In Scenario 0, crop farmers did not produce mixed crops, and livestock farmers
 455 were not interested in using them if they were not sorted.

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

Group	Pamiers group		Mirepoix group	
	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

457 * (+) are meant for « supply » whereas (-) are meant for « demand »

458

459 3.2.2. Step 2.2. Analysis of farmers' motivations to join the group

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

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

481 Farmers were motivated to build relationships with their neighbors, but mainly in the Mirepoix
482 group. In the Pamiers group, crop farmers in valley areas were motivated more by their gross
483 margin than by social aspects. As a crop farmer in the Pamiers group explained, *"We sell to*
484 *the cooperative. It's easier than coordinating ourselves with livestock farmers."* In the
485 Mirepoix group, farmers focused on (re)building strong relationships between crop farmers
486 and livestock farmers, who do not usually work together. As crop farmer C3 in the Mirepoix

487 group explained about his interest in being part of a group: “For me, it is more to provide
 488 solutions to livestock farmers, who are disappearing.”

489

490 3.3. Step 3 – Group design of scenarios using Dynamix

491 3.3.1. Sub-step 3.1: Technical component of the scenarios designed

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

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

Group	Pamiers		Mirepoix	
	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)
Total by product				
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

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

507 In the Pamiers group, crop farmers were rather interested in producing mixed crops (e.g. a
508 pea-barley mix to harvest as grain) and new protein crops in general to diversify their
509 rotations and limit mineral nitrogen input needs and pesticides. Still, regarding technical
510 issues and risk aversion, they preferred to sell soybean that they already produced to
511 livestock farmers. The livestock farmers were not interested in continuing to use soybeans,
512 since they had no way to toast or press it, and preferred pea or faba bean in their feeding
513 system. Crop farmers were eager to maintain current levels of maize production, since they
514 were highly skilled in producing it, rather than introducing triticale, which livestock farmers
515 demanded more. This may explain the high supply-demand imbalance in cereals in Scenario
516 2 that remained despite further discussions. In addition, livestock farmers required straw, but
517 crop farmers wanted to keep it on their soils to improve the organic matter content.

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

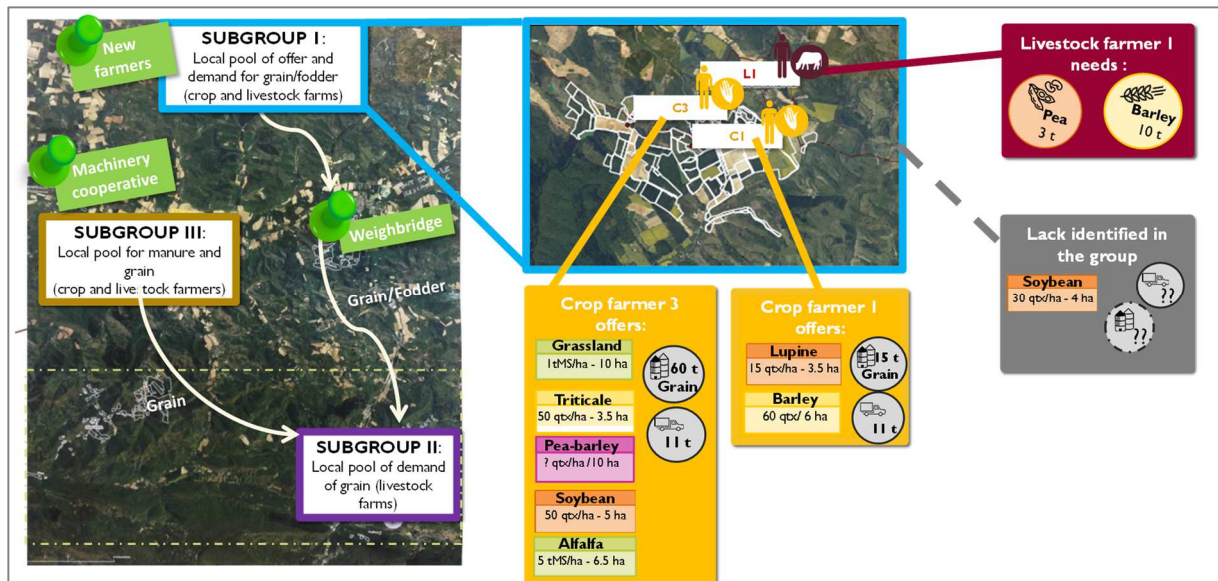
529

530 **3.3.2. Sub-step 3.2. Organizational dimension of the scenarios designed**

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

541 The Mirepoix group agreed on polycentric governance and specified three subgroups in their
542 group map (Figure 5). Subgroup I consisted mainly of crop farmers who would produce and
543 store the new crops, which would be delivered to subgroup II, which consisted of livestock
544 farmers who were not self-sufficient in feeding. Subgroup III was intermediate between the
545 two other subgroups and included cereal production and straw-manure exchanges. To
546 coordinate these subgroups, farmers considered co-creating one (or more) local platform(s)
547 to store, weigh, evaluate quality, write invoices and transport. A platform could be created on
548 a farm with available storage, could be purchased together or could depend on an existing
549 organization such as a cooperative for sharing machinery. This organization would enable
550 farmers to depend less on intermediaries, even though it would be more time-consuming at
551 the beginning than pairwise relationships or centralized organization through an existing
552 cooperative. Livestock farmer E2 stated: *“We must not keep the same mindset of livestock
553 farmers versus crop farmers.”*

554



555

556 **Figure 5.** Map of the group organization suggested by farmers in the Mirepoix group while playing the
557 serious game.

558 On the group organization map, farmers suggested three main subgroups that highlighted the supply
559 (rectangular tokens) and demand (round tokens) of agricultural products. Subgroup I consisted mainly
560 of crop farmers who could produce new crops, including protein crops (lupine and soybean), harvest
561 grasslands to make hay (alfalfa and permanent grasslands) and already produced mixed crops (pea-
562 barley) and cereals. White arrows represent flows from the new crops supplied by subgroup I to
563 subgroup II, which consisted of livestock farmers who were not self-sufficient in feeding. The focus on
564 subgroup I highlights i) the supply of grain and fodder (rectangular tokens) from crop farmers C1 and
565 C3 and the logistical storage and transport options they could provide for the group, ii) the demand for
566 grain by livestock farmer L1 (round tokens) and iii) the lack of certain protein crops and logistical
567 options highlighted by the group that subgroup I farmers might solve. Farmers in subgroup III also
568 planned to produce maize and wheat for livestock farmers and to exchange manure between crop
569 farmers and livestock farmers. Green pins represent new stakeholders, and dash-dotted lines
570 represent uncertainty in the scenarios as new stakeholders are included in the group or as farmers
571 design new logistical tools. (2-column-fitting image)

572

573 **3.4. Step 4 - Scenario simulation and multicriteria evaluation**

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

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

593 **3.5. Step 5 – Group evaluation of the scenarios and perspectives**

594 During group evaluation of the scenarios, farmers agreed with the technical aspects but
595 highlighted the need to obtain and share new practical skills to integrate crops and livestock
596 adequately. Farmers focused particularly on the need for technical information to explore
597 options for species mixtures to sow as cover crops that would be grazed efficiently or sold
598 standing. Obtaining this information requires regular meetings and training for the entire

599 group and technical institutes that are part of the project. Concerning legal issues, we
600 specifically discussed the current legislation that bans selling crops directly from farmer to
601 farmer without an official agreement, such as via a “collection and storage organization”. A
602 cooperative could weigh grain and write invoices; as one crop farmer said, *“As for*
603 *exchanges, if you don’t do them by the rules, one day there will be trouble.”* Fodder was not
604 considered a limiting factor, but grazing or renting of grasslands should be included in
605 contracts.

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

614 **3.6. Step 6 – Implementation of the scenario**

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

623 For logistics and storage, one relevant option is to involve existing organizations, such as
624 local machinery cooperatives or agricultural contractors. Since we decided to add more

625 groups, we discussed having small groups based on a local machinery cooperative for
626 logistical aspects, but coordinating advising, legal and prospective discussions at a larger
627 level that included all groups. An unexpected result is that the crop-livestock farmer in the
628 Mirepoix group became president of a local association of livestock farmers who plan to
629 finish young cattle with only non-GMO local feed and sell their meat locally. Livestock
630 farmers in this group are highly motivated to obtain local self-sufficiency and to work
631 together, since they already have strong relationships. A new group thus emerged from this
632 group of livestock farmers. The most motivated conventional crop farmers in the Pamiers and
633 Mirepoix groups are included in this new group. A new organic subgroup was created with
634 organic farmers from the Mirepoix group. Both groups have been certified as “Groups of
635 Economic and Environmental Interest”, i.e. groups of farmers funded by the French Ministry
636 of Agriculture for knowledge exchange and collective infrastructure (Lion, 2015) and planned
637 to return to step 3.

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

646 The conventional subgroup engaged in a new dynamic with a group of livestock farmers
647 selling their young cattle meat locally. These cattle farmers wanted to include local feed from
648 Ariège in their specifications. They organized a collective meeting during July 2020 and
649 decided that they were lacking some new actors in their group, especially to provide a local
650 concentrate that would be already balanced for some of the livestock farmers, who did not
651 want to make the mix themselves and did not have the material for on-farm feed production.

652 This meeting led to the new multi-partner project FAAB (Feed production for livestock in
653 Ariège) involving a broader set of actors: farmers, advisers, research and local cooperatives.
654 This project is ongoing.

655

656 **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	<ul style="list-style-type: none"> Local inclusion of new crops with little experience with them Livestock farmers testing new feeding systems 	<ul style="list-style-type: none"> Test new crops in rotations Visit farms that produce new crops Visit farms self-sufficient in feeding 	<ul style="list-style-type: none"> 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 groups’ farms
Logistics and storage	<ul style="list-style-type: none"> Identify space for storage Identify ways to transport the products 	<ul style="list-style-type: none"> On-farm storage when possible Use intermediary agricultural contractors or cooperatives Rely on existing machinery cooperatives 	<ul style="list-style-type: none"> Interviews planned with local and machinery cooperatives Implementation of a pilot operation for manure composting and transport
Legal framework of the sales	<ul style="list-style-type: none"> How to sell products legally 	<ul style="list-style-type: none"> Provide legal framework for all contracts Capitalize on existing examples of farmer-to-farmer sales 	<ul style="list-style-type: none"> Visits with farmers or groups that legally manage storage and invoicing Diffusion of examples of existing contracts for grazing or renting of grasslands
Trust and schedule	<ul style="list-style-type: none"> Different timing for crop and livestock farmers Lack of trust 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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.

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

659

660 **4. Discussion**

661 **4.1. The Dynamix serious game as a key component of the participatory approach**

662 ***4.1.1. A spatially-explicit board game to co-design technical and organizational*** 663 ***scenarios***

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

681 The main innovation compared to previous studies on the topic was the explicit
682 representation of logistical needs in the board game (i.e. transportation and storage)
683 depending on the topography, roads and location of farms on a map. Previous studies on the
684 topic (Moraine et al., 2017; Regan et al., 2015) mentioned the logistical dimension and group
685 organization as major lock-ins, but considered only supply-demand balances and technical
686 aspects. In our study, the map and logistics cards promoted in-depth spatial description of
687 logistical organization, which facilitated discussions of two governance options in the two
688 groups. These boundary objects encouraged discussions that focused on transaction costs,
689 such as operational costs and implementation (e.g. formal contracts, logistical planning,
690 management needs). Asai et al. (2018) highlighted these aspects as key issues for crop-
691 livestock integration beyond the farm level. Future steps could include quantifying costs of
692 investing in group storage or optimizing transportation routes.

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

705 We worked closely with two groups of farmers which could be considered as two polycentric
706 groups or “nodes”. However, we did not consider how these groups might be combined with
707 upper-scale governing authorities levels as recommended by Biggs et al. (2012). Getting

708 inspiration from outside agriculture would help us make process in this direction, especially in
709 the way of including new actors such as cooperatives. Autonomy in decision being a key
710 objective for livestock farmers in this process, the integration of new actors must be thought
711 through and largely discuss in collaboration. As highlighted by Romera et al. (2020), studies
712 in industrial ecology have already considered the inclusion of economic firms which could
713 help lowering input and logistical costs and should be included in a territorial network. Here, it
714 will be relevant to consider not only the agricultural sector in a food system transition but to
715 see how to build a coordinated network at the territory level, which could articulate
716 relationships between farmers and other actors in the territory while achieving cultural and
717 socio-economic benefits in a so-called AES (Agroecological Symbiose) (Koppelmäki et al.,
718 2019). The FAAB project mentioned earlier in section 3.6. supports this perspective, as
719 cooperatives are contributing along with other local actors.

720

721 ***4.1.2. A relevant decision support tool applicable to other farmer groups***

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

727 Dynamix meets the conditions required for a DSS to be effective for design in agriculture, as
728 Rose et al. (2016) highlight. First, DSS should be simple to use to be transferable to advisors
729 and other case studies. The supply-demand balance and multicriteria evaluation developed
730 in Dynamix are based on standard technical-economic farm data used by agronomic
731 advisors. Fewer details are required because advisors already have farm data about the
732 feeding system, while the set of management practices, rotations and field maps are
733 available from EU Common Agricultural Policy declarations. The parameters used to

734 simulate the scenarios come from standardized databases and thus can be adapted easily
735 over time. Dynamix was designed with advisors to ensure that output data required
736 corresponds to their needs and renders the tool easily transferable. An additional step to help
737 advisors use Dynamix will be to transfer the model to a free web platform and make it
738 possible to update its database with online agricultural data such as those from agricultural
739 censuses and EU's Farm Accountancy Data Network, or from databases and tools that
740 advisors already use at the farm level. A multi-language version, including English, will be
741 developed as well.

742

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

756

757 DSS developed by researchers often remain unused because they are not relevant to users.
758 We developed Dynamix with end-users to ensure that the evaluation met farmer
759 expectations. As Martin et al. (2016) mentioned, it is important for farmers to obtain
760 multicriteria assessments of economic, environmental and social performances at the
761 individual farm and group levels, as well as over time. Through Dynamix, farmers can choose

762 and rank indicators from a wide range of options at both individual farm and group levels,
763 which helps them to render the scenarios more concrete and feasible (Lamarque et al.,
764 2011). The Dynamix model allows a large range of indicators to be calculated with minimum
765 time and cost, as long as data are already available for each farm and group of farms. While
766 this large range is of interest for researchers willing to explore the multiple impacts of the
767 scenarios co-designed, integrating and interpreting these indicators and related trade-offs is
768 a complex task. Thus, each specific group of farmers is given the opportunity to choose the
769 specific set of indicators they would like to discuss during Step 5 to focus on the most
770 important criteria for them, e.g. decreasing input use while not increasing workload and
771 logistical costs too much in our groups here. By doing so, interpretation, trade-off analysis
772 and scenario adjustment remain feasible during a workshop to verify whether the changes
773 made in the scenarios correspond to the farmers' personal objectives, such as those
774 regarding work organization.

775

776 **4.3. The importance of the entire participatory approach for fostering integrated crop-** 777 **livestock systems**

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

786 First, the participatory and iterative approach enabled new stakeholders to be included after
787 step 3, when farmers suggested them, especially to address logistical aspects (e.g. local
788 cooperative). Allowing new stakeholders into the participatory approach is highlighted as a

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

805 Second, explicitly considering trade-offs between individual farm and group levels
806 encouraged discussions about equity and establishing trust. This avoided a decrease in
807 individual farm self-sufficiency in local scenarios and a loss of autonomy in decision making,
808 unlike in other studies of crop-livestock integration beyond the farm level (Regan et al.,
809 2017). Group discussions about establishing a price, or at least floor and ceiling prices, can
810 increase equity in sharing the benefits of the integration planned in the scenarios. A future
811 step could include sensitivity analysis of scenario outputs to price ranges for each product
812 based on climate conditions and market trends. This analysis could help farmers to decide
813 fair prices for the entire group. Equity, which lies at the heart of such group projects, can also
814 be addressed by establishing trust (Fisher, 2013), which is promoted by using the serious
815 game.

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

833

834 **Conclusion**

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

843

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848

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