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# 1 **A methodology for redesigning agroecological radical production systems at the farm level**

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8

## 9 **Abstract**

10 A redesign process at the farm level may be required for agricultural production systems to  
11 evolve in a manner that reduces their environmental and health impacts. This process leads to  
12 imagining configurations described as “radical” because they reach beyond the limits posed by  
13 the substitution of synthetic inputs by natural ones. An assessment of the possible effects of  
14 these configurations on farm functioning and performance is required to inform stakeholders  
15 about the advantages of testing and implementing them. This study describes an approach for  
16 designing and assessing such configurations that involves researchers, technicians and farmers.  
17 Some of these stakeholders can play the role of designers, who lead the redesign process, and/or  
18 experts, who provide references and knowledge throughout the exercise. The approach is based  
19 on six principles (evaluation, plausibility, precision, flexibility, diversity, iteration) and includes  
20 eight steps. Based on a diagnosis of the production context (step 1), some ideas of radical  
21 production system are imagined (step 2), which define the kind of experts to be involved (step  
22 3). A farm, virtual or real, then is selected and characterized as a case study (step 4), and the  
23 specific objectives driving the farm's redesign process are described (step 5). Scenarios are then  
24 designed and characterized (step 6), quantitatively assessed using a simulation tool dedicated  
25 to the kind of production system studied (step 7), and compared in order to feed debates between  
26 designers and experts on the merits and limits of the various options designed (step 8). Steps 6

27 through 8 may be repeated as new ideas emerge. This methodology is illustrated with the case  
28 of a farm specialized in apple production on which a sheep unit is introduced to reduce pesticide  
29 use by ensuring grass management and reducing pest pressure. Two scenarios are designed  
30 according to the kind of sheep management. CoHort software was used to assess the two  
31 scenarios in terms of economic performance, frequency of pesticide use, and farm work  
32 organization. The limits and values of this redesign process are discussed regarding the  
33 hypothesis that must be made to characterize virtual biodiversity-based systems, the kind of  
34 involvement expected from farmers, and the opportunities provided by moving from the farm  
35 to territory scale in the case of crop-livestock systems. This redesign approach can potentially  
36 be applied to many topics, ranging from the consistent combination of agroecological practices  
37 to futuristic scenarios involving robots.

38 **Key words:** Simulation; Assessment; Participatory; Apple; Sheep

## 39 **1. Introduction**

40 To cope with the negative impacts of agricultural practices on the environment, human health  
41 and natural resources, production systems must evolve. Several authors have identified trends  
42 of ecological modernization in agriculture that are in response to this urge to develop more  
43 sustainable practices. In their review, Duru et al. (2015) organized these trends into two  
44 categories: efficiency-substitution and biodiversity-based agriculture. The first aims to improve  
45 the efficiency of how inputs such as fertilizers and pesticides are used, or to substitute inputs  
46 with biological or environmentally less harmful ones. The second aims to develop ecosystem  
47 services instead of using these synthetic inputs. Production systems from the first category may  
48 not be able to solve environmental problems such as biodiversity loss, erosion, degradation of  
49 air, water and soil quality, or decreased natural resources. They are considered to be a ‘weak’  
50 form of ecological modernization (Horlings and Marsden, 2011). In contrast, biodiversity-based  
51 systems are considered to be more sustainable since they seek to develop diversity in time and

52 space to enhance functional complementarities in resource use and biological regulation.  
53 Diversity is a key to reach sustainability and resilience (Lin et al., 2011).

54 The majority of production systems belong to the first category (Pretty, 2018). Indeed, several  
55 factors, known as "lock-in" effects, act to block the development of biodiversity-based systems  
56 (Cowan and Gunby, 1996). For example, biodiversity-based systems often require specific  
57 resources at the farm level such as equipment, land or capital. If these are unavailable, additional  
58 investments must be made (Pissonnier et al., 2016). At the supply chain level, structural changes  
59 also may be required to sell the new crops produced by biodiversity-based systems (Meynard  
60 et al., 2012). Farmers would rather evolve towards systems that are less risky, less  
61 transformative and better known (Dupré et al., 2017).

62 To develop biodiversity-based systems, dedicated design methodologies are needed to tackle  
63 these potential lock-in effects at both the farm and supply chain level (Cowan and Gunby, 1996).  
64 In this respect, redesign methodologies seem relevant since they encourage a paradigm shift  
65 and a more holistic view of the system and its interactions with its socio-economic context  
66 (Pretty, 2018). Indeed, redesigning production systems includes reconsidering the long-term  
67 objectives, structure and functions of the production systems (Hill and MacRae, 1996). These  
68 methodologies can be classified according to the scale of the system studied: the cropping  
69 system (Colnenne-David and Doré, 2015; Loyce and Wery, 2006), the farm (Carberry et al.,  
70 2002; Dogliotti et al., 2014) or the territory/landscape (Ceschin and Gaziulusoy, 2016). The  
71 farm scale is strategic point to conduct this process since biodiversity-based systems involve  
72 structural changes and need specific resources impacting various components of a farm  
73 (Pissonnier et al., 2016). It also allows consideration of a farm's socio-economic context and  
74 the lock-in effects this context produces.

75 Assessing the outputs of the redesign processes is important to identify where to progressively  
76 improve the systems designed and how to organize transitions towards these systems by taking

77 into account the uncertainties that characterize them (Debaeke et al., 2009; Pisonnier et al.,  
78 2017). The tools used to support and assess the redesign process are diverse depending on the  
79 issue and the stakeholders involved: modelling (Ould-Sidi and Lescourret, 2011), experiments  
80 (Le Bellec et al., 2012), qualitative assessment through workshops and discussions (Moraine et  
81 al., 2017) or boundary objects such as scale models (Klerkx et al., 2012). A scenario-based  
82 methodology applied to virtual situations helps to learn about the potential impacts of various  
83 alternatives on farm performance (Bood and Postma, 1997). In this respect, simulation tools are  
84 particularly useful since they allow an expanding number of alternatives to be investigated  
85 while providing an integrative representation of a farm (Le Gal et al., 2011). This virtual process  
86 helps to save time and reduce trial and error experiments, which are risky at the farm level. It  
87 may involve a diversity of stakeholders with variable profiles, kinds of knowledge (scientific,  
88 technical and empirical) and degrees of participation (Stelzle et al., 2017), especially when the  
89 process focuses on radical changes (Toffolini et al., 2017).

90 This study presents an approach intended to be used by managers of redesign processes in the  
91 field of agroecology to assess the consequences of radical transformations of farm production  
92 systems. The aim is to encourage and explore new types of combinations of activities and  
93 crops/animals. It takes into account the farm scale and its socio-economic context, and evaluates  
94 the possible outputs of radical production systems both qualitatively and quantitatively through  
95 the use of a simulation tool. This methodology includes eight steps that are successively detailed  
96 in Section 2. Its implementation is illustrated in Section 3 using the case of a farm specialized  
97 in apple production where a sheep unit is introduced as a potential way to move towards more  
98 agroecological farming (Herrero et al., 2010). Such a crop-livestock combination remains rare  
99 and little studied for perennial crops (see (Niles et al., 2018) for viticulture-sheep integration),  
100 and in this respect constitutes a radical configuration for the crop component (Simon et al.,

101 2017). The value and limits of this methodology are discussed regarding both its feasibility and  
102 its capacity to contribute to the farmers' dynamics towards agroecological transition.

## 103 **2. An eight-step redesign process**

### 104 *2.1. Guidelines of the process*

105 The approach undertaken aims to assess the consequences of radical scenarios on farms, with  
106 the purpose of then encouraging and exploring transitions towards these new types of  
107 combinations of activities and crops/animals. The redesign process carried out in this study was  
108 based on the following six principles:

109 (i) Evaluation: in redesign methodologies, radical production systems involve important  
110 structural changes at the farm scale. An assessment of their performance is therefore required  
111 to better organize transitions. This can be both qualitative and quantitative and can require the  
112 formulation of hypothesis, especially regarding quantification.

113 (ii) Plausibility: actual farms and data should be used to make the results plausible and enable  
114 a more concrete discussion of the redesign outputs;

115 (iii) Precision: production systems should be described in detail to be able to discuss their actual  
116 implementation, and base discussions on results considered reliable by experts in the field;

117 (iv) Flexibility: flexibility is required to adapt to the diverse situations encountered (Dedieu et  
118 al., 2011). Flexibility makes it possible to imagine a variety of redesigned production systems  
119 integrating different combinations of productive activities according to various combinations  
120 of resources. The different steps and tools on which the process will be based cannot be specific  
121 to a crop, a context or a farm;

122 (v) Diversity: diverse and knowledge resources should be involved to enrich the production  
123 systems designed, improve their assessment and cope with a possible lack of scientific data

124 regarding biodiversity-based systems. The farmers may or may not be included in the process,  
125 depending on their ability to rise above their constraints which might limit the production  
126 systems they consider (Lançon et al., 2008). To ensure access to a diversity of data, the choice  
127 and description of redesigned production systems should be made based on both a literature  
128 review and the consultation of experts.

129 (vi) Iteration: one should rely on iterative rounds between the different phases to improve and  
130 modify various configurations of the same production system according to the constraints,  
131 questions and new hypotheses raised during the process (Debaeke et al., 2009)

## 132 *2.2. Implementing the process*

133 The process consists of eight steps aiming to design and evaluate radical innovative production  
134 systems at the farm scale (Figure 1). The process is initiated and managed by stakeholders  
135 interested in implementing this objective, named ‘designers’ hereafter. They may ask resource  
136 persons, named ‘experts’ hereafter, to contribute their specialized knowledge to specific steps  
137 of the process. Anyone, such as academics, researchers, PhD students or professionals (e.g.,  
138 farmers, technical advisors), can be a designer or an expert depending on his/her role in the  
139 process.

### 140 *Step 1. Initial diagnosis of the production context*

141 Based on an analysis of the functioning and performance of the production system studied,  
142 designers first identify opportunities for improvement, and start generating interactions between  
143 designers and experts who could potentially be involved in the redesign process (Le Bellec et  
144 al., 2012). This diagnosis also helps to find potential innovative practices that have already been  
145 developed on farms (Salembier et al., 2016) or that have been tested in technical centres and  
146 experimental stations (Simon et al., 2017).

147 The diagnosis, which can be done in areas where research and development projects are  
148 ongoing, involves a description of the soil and climatic conditions, socio-economic context and  
149 territorial resources (e.g., input suppliers, marketing channels and support services, research  
150 centres and knowledge accessibility), and public regulations. It also covers farm diversity in  
151 terms of objectives, strategies of production, practices implemented and the technical-economic  
152 performance of the production system studied. Indeed, these different components influence  
153 the identification, value and potential development of new practices (Nolot and Debaeke, 2003).

154 This set of information is collected from a range of sources: (i) bibliography of previous studies  
155 carried out in the area, (ii) regional reports on specific crops, regional statistics on volumes and  
156 practices, edited by agricultural chambers or public institutions, (iii) interviews of various  
157 stakeholders working in the area, such as farmers, technical advisors, input suppliers and  
158 product buyers, (iv) in-depth farm surveys to analyse farm functioning and to understand  
159 farmers' strategies and management processes.

#### 160 *Step 2. Identifying a radical production system*

161 During the second step, designers identify 'radical' production systems that may potentially  
162 represent the transition of the current farms towards biodiversity-based systems. These  
163 innovative ideas may take several directions, for instance the introduction of new technologies  
164 such as robots to reduce the use of pesticides and labour, or the combination of new species that  
165 develop complementary environmental services and interactions between pests and auxiliaries,  
166 improve the use of space, and provide additional income for farmers (Nair, 2011; Moraine et  
167 al., 2016). The ideas can emerge from the diagnosis in step 1, as well as from a bibliographic  
168 search on innovative design studies in other production areas or similar production systems.

169 These radical systems are not restricted to a sum of innovative practices. They may require  
170 specific resources such as equipment, labour, capital, and land, specific ecological and technical

171 knowledge, the development of new activities such as processing and marketing, or the redesign  
172 of plots by implementing hedgerows, for example (Gouttenoire et al., 2013; Toffolini et al.,  
173 2017). These various components have to be listed in order to prepare the next step.

#### 174 *Step 3. Identifying the required experts*

175 The third step aims to identify the resource persons likely to contribute to the conceptualization  
176 of the selected radical production system, its deployment as scenarios to be simulated, and their  
177 detailed qualitative and quantitative characterization. The principle of source diversity is  
178 applied in order to identify these experts from different categories (farmers, academics and PhD  
179 students, researchers, professionals), who can provide references and knowledge needed to  
180 design each scenario in the context studied. Experts can be identified throughout the first and  
181 second steps. They can propose other experts to cover a large range of skills and knowledge.

#### 182 *Step 4. Choosing and characterizing a farm case*

183 Design in agriculture at the farm scale is based on (i) real and existing farms identified during  
184 the first diagnosis step, (ii) experimental farms linked or owned by research institutes, schools,  
185 technical centres or which are independent, (iii) hypothetical or theoretical farms created by  
186 designers, or (iv) typical or representative farms, derived from types that are identified during  
187 the initial diagnosis (Le Gal et al, 2011). During this fourth step, designers have to choose  
188 between these options according to the production system under study, the farm cases, if any,  
189 they have analysed in step 1, and the projected use of their study outputs. For instance, selecting  
190 a real farm would be relevant when a detailed operational description of the radical scenario  
191 seems useful, combined with a use of the outputs by stakeholders other than the designers  
192 themselves.

193 Whatever the case, characterizing the initial state of the selected farm case will require a  
194 description of the farm's resources in terms of capital, labour, equipment and land, its various

195 activities and sets of practices per activity, its technical and economic performance (yields,  
196 costs, selling prices), and its interactions with its environment. All of these items must be  
197 defined in a systemic and consistent way, a process easier to conduct on a real farm that already  
198 has been analysed than on a virtual one where every interaction between items has to be  
199 investigated.

#### 200 *Step 5. Defining the objectives of the radical production system*

201 To move from a generic objective (designing a biodiversity-based production system) to a  
202 radical production system applied to a farm case, specific objectives must be defined that will  
203 then drive the design of the simulated scenarios. Past studies show that farmers balance various  
204 economic and environmental concerns when making decisions (Pissonnier et al., 2016; Dupré  
205 et al., 2017). Environmental objectives drive the selection of which ecological processes and  
206 ecosystem services to favour (Colnenne-David and Doré, 2015), whereas economic objectives  
207 drive the configuration of the production system in order to achieve a given income with a given  
208 risk level. Combining these two objectives is instrumental for guiding the selection of decision  
209 rules, activities and practices to be implemented in each scenario. The process can be based on  
210 a farmer's initial objectives when carried out on a real farm.

#### 211 *Step 6. Defining and characterizing scenarios*

212 The next step consists in defining and characterizing scenarios linked to both the radical  
213 production system and the farm case selected. Each scenario consists in a specific configuration  
214 of the farm that must (i) respect the economic and environmental objectives defined in step 5,  
215 (ii) take into account the context that can prevent or encourage the development of specific  
216 activities or practices, (iii) start from the initial configuration and management of the farm, and  
217 (iv) respect the biological needs of the crops and animals that it includes. Each configuration is

218 then defined as a set of qualitative rules and decisions translated into activities and practices  
219 characterized quantitatively.

220 During this step, experts and designers need to mobilize all their knowledge and expertise to  
221 set up a consistent scenario taking into account possible interactions between the objectives,  
222 the farm resources, the selected activities and practices with their associated performances, and  
223 the farm context. Complementary information may be needed to make consistent choices, such  
224 as the existence of specific supply chains in the area that were not taken into account in the first  
225 step. This information can be found through additional interviews or technical documentation.  
226 The biotechnical component may require an extra literature review regarding the crop/animal  
227 needs and the role of wild species for enhancing ecosystem services.

228 This step is instrumental to the entire redesign process to provide realistic configurations and  
229 reduce quantitative errors. It often requires moving back and forth between all of the steps in  
230 order to produce satisfying scenarios. This process is driven by the qualitative assessment that  
231 both designers and experts carry out to check the consistency of the scenario and to correct any  
232 gaps.

### 233 *Step 7. Quantitative assessment of each scenario*

234 When a scenario seems qualitatively satisfying and has been quantitatively characterized, it can  
235 be simulated in order to be quantitatively assessed. This seventh step allows the consequences  
236 of the scenario on the chosen farm's performance to be assessed. CoHort, a simulation tool  
237 operating at the farm level, is used for this purpose (Pissonnier et al., 2017). The tool has been  
238 developed and used to support fruit tree growers in moving towards alternative strategies but it  
239 is not specific to a context or a crop. A farm is characterized in CoHort by its available resources  
240 (equipment, manpower, land, capital), the time consumed by farming and non-farming  
241 activities, and the practices implemented in all or part of the farming activities, taking into

242 account inputs, equipment used and time consumed (Figure 2). Using these input data, CoHort  
243 calculates the economic performance and pesticide use frequency (Treatment Frequency Index  
244 - TFI) of the farm represented and its monthly balance between supply and demand for labour.  
245 Each scenario corresponds to a unique configuration of the farm characterized by the values of  
246 the set of input variables (Le Gal et al., 2013) (for a detailed description of the tool see  
247 Pissonnier et al., 2017). The radical scenarios are assessed and compared to the initial situation  
248 of the farm, unless the farm is a theoretical farm or has been recently established.

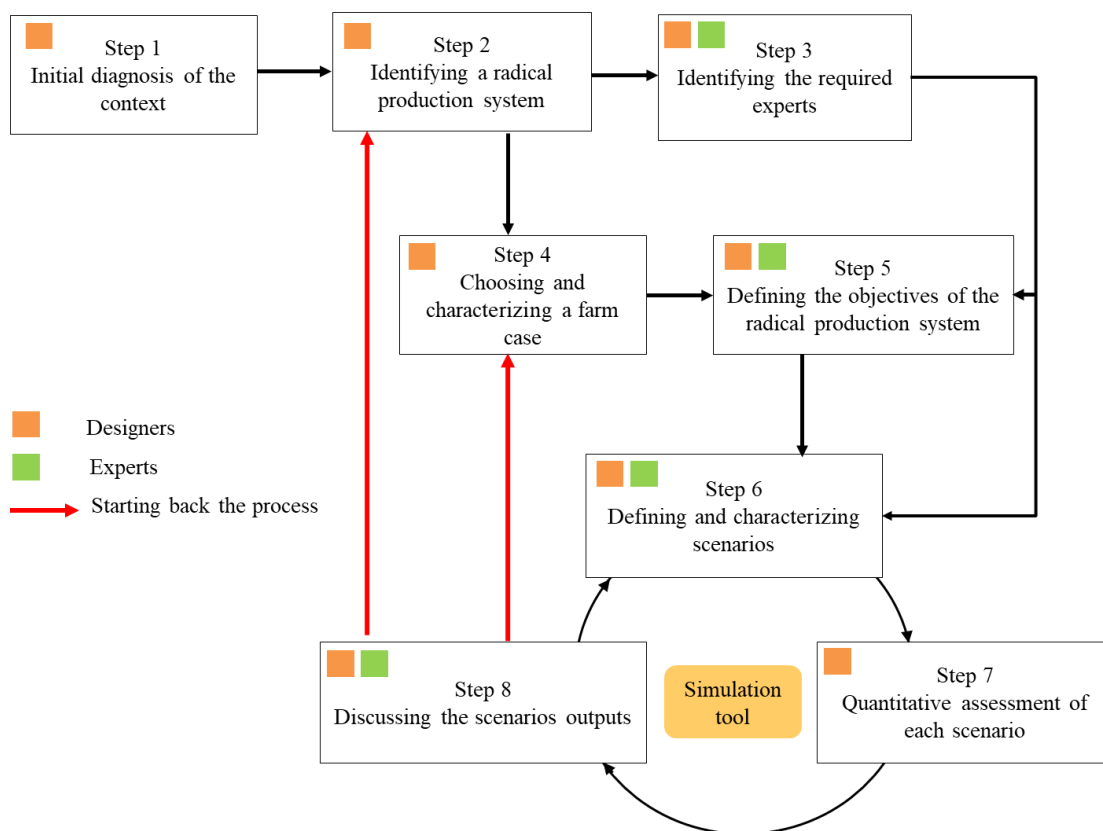
249 The configuration of the tool influences the type of references needed. CoHort needs a  
250 quantification of the time spent (in days or hours) for all activities and practices implemented,  
251 and the costs of all the inputs and equipment used. The availability of references depends on  
252 the originality of the scenario and the possibility to find similar farm configurations in real life.  
253 The search field can then be enlarged to gather as many references as possible in both scientific  
254 and grey literature (e.g., technical reports, unpublished data or papers, experts' interviews,  
255 testimonies, websites). However, for biodiversity-based systems, gaps in knowledge persist  
256 concerning ecological processes and their interactions with the landscape, agricultural  
257 practices, and the resulting biological regulation of pests (Martin et al., 2016). Some data or  
258 information may be unavailable or unknown, leading to the formulation of new hypotheses.

#### 259 *Step 8. Discussing the scenario outputs*

260 The final step in the process is to discuss the merits and feasibility of the scenario simulated  
261 with regard to the initial objectives based on the outputs of the simulations. These discussions  
262 involve all of the actors (experts and designers) who have contributed to the scenario's design  
263 and description. Both the results of the quantitative and qualitative assessments are used in the  
264 discussion. They may show some discrepancies with the initial objectives, for instance an  
265 income inferior to the one expected or a use of pesticides that remains too high. When that is

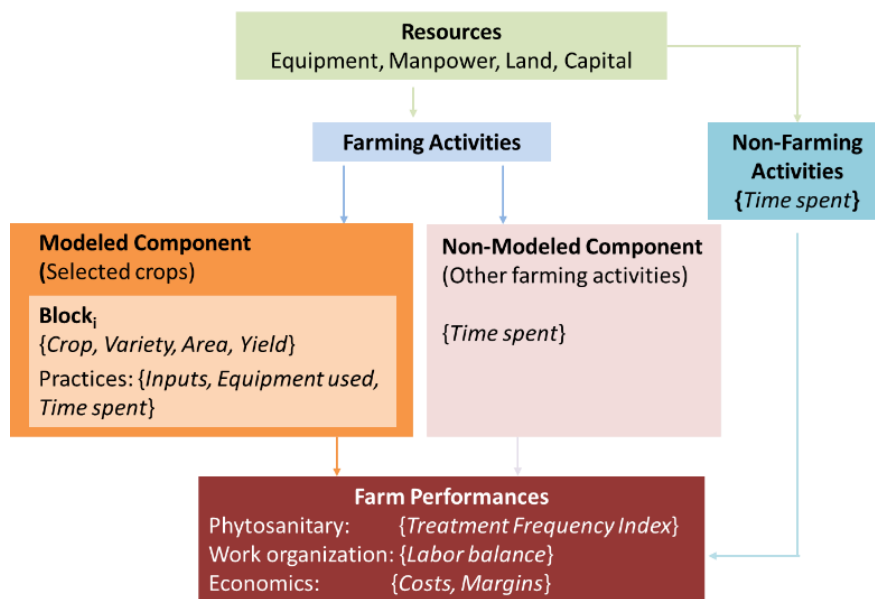
266 the case, both designers and experts can return to step 6 to design a new scenario likely to  
267 achieve these objectives.

268 This iterative process enriches the discussions taking place between stakeholders throughout  
269 the redesign approach. The process concludes with an assessment of the initial idea's value and  
270 the conditions of its potential implementation in the selected case. The redesign process can  
271 then be eventually reset by changing the initial idea (back to step 2), or changing the farm case  
272 (back to step 4) to extend the evaluation context.



273

274 Figure 1. The eight steps of the redesign process and the actors involved.



275

276 Figure 2. Structure of CoHort (source: Pissonnier et al., 2017)

### 277 3. Implementing the approach on a real apple farm

#### 278 3.1. From the diagnosis to the choice of experts (steps 1-3)

279 Apple crops are susceptible to numerous pests and diseases. Farmers try to manage these by  
 280 spraying a high amount of pesticides in order to secure their yields (Drogué and DeMaria,  
 281 2012). However, consumers are demanding a decrease in the use of pesticides that have negative  
 282 impacts on human health and environment. Redesigning these production systems with an  
 283 objective of reduced pesticide use is thus a critical challenge, and one which was addressed in  
 284 the course of a research project on the management of protection practices in apple production.  
 285 This redesign process, which was led by a PhD student and a researcher who are both  
 286 specialized in farm management, provides an illustration of how the approach described in this  
 287 article can be put into practice.

288 The research was carried out near Montpellier (France), where a hot and dry climate makes it  
 289 difficult for growers to manage pests. A diagnosis of their practices was conducted that was  
 290 based on a review of technical reports and semi-structured interviews with stakeholders. The  
 291 interviews, which were conducted with ten growers working through cooperatives and six

292 independent growers, had three objectives. The first was to understand the growers' current  
293 production strategies, while the second was to analyse the diversity of practices that had been  
294 developed in the area. The third was to identify the factors influencing growers' decisions and  
295 preventing the development of alternative practices (see Pisonnier et al., 2016 for more  
296 details). Table 1 summarizes the characteristics of the region.

297 This diagnosis showed that many growers already had implemented some alternative practices,  
298 such as the use of insect traps or natural pesticides (copper, sulphur). However, when these  
299 alternative practices were more costly or labour demanding than their previous practices, or  
300 increased the risk of failing to meet their quantity and quality standards, growers were reluctant  
301 to proceed with them further. These constraints were particularly sensitive for growers  
302 belonging to cooperatives dealing with supermarkets. This lock-in effect led researchers to  
303 explore radical production systems that could potentially lift these constraints while favouring  
304 agroecological farming through the development of both metabolic and regulation services  
305 (Herrero et al., 2010; Bonaudo et al., 2014). Based on some experiences implemented by  
306 independent growers in the region, the choice was made to investigate the introduction of an  
307 animal flock on a farm specialized in apple production. Such an innovation would require  
308 specific resources and strategies for the installation, management and marketing of the flock  
309 (Ryschawy et al., 2017), while its impact on orchard management needed to be precisely  
310 assessed.

311 A radical production system combining a sheep unit with an apple unit was then designed. It  
312 was decided that the farmer would own the flock rather than periodically host one belonging to  
313 a separate livestock farmer in order to be autonomous and to be consistent with a radical  
314 strategy. Experts were then contacted for their knowledge regarding this system, including a  
315 researcher specialized in sheep production and a technician from INRA (National Institute of  
316 Agricultural Research) specialized in orchard-sheep systems. Grey literature and technical

317 documents were gathered, particularly documents on grass management and sheep management  
318 (technical aspects of the flock management, transformation and sales). These documents were  
319 written by agricultural chambers, technical institutes or associations. Documentation on the  
320 integration of sheep flocks into fruit tree crops was also gathered, based on project reports and  
321 a student report characterizing these forms of integration based on testimonies.

322 The information collected indicated that this apple-sheep association offered two benefits that  
323 could reduce the use of synthetic inputs: (i) by grazing the orchards, sheep reduce weed  
324 pressure, allowing a maintenance of grass cover on the orchard and thus a decreased use or  
325 elimination of herbicides (Geddes and Kohl, 2009); and (ii) by trampling dead leaves, sheep  
326 reduce disease pressure (decrease of the scab (*Venturia inaequalis*) inoculum stock) (Horner  
327 and Horner, 2002), and by consuming rotten apples, they reduce pest pressure (decrease of the  
328 codling moth *Cydia pomonella* population) (Enkhtur et al., 2017).

329 The flock's fertilizer contribution was not considered, although it could account for 17 N per  
330 hectare (Bloor et al., 2012), because this potential fertilizer supply could not be managed easily  
331 by the grower. Indeed, dejections can be distributed unequally at the plot scale, preventing some  
332 trees from access to nutrients. Moreover, the incorporation of dejections into the soil depends  
333 on insect populations, which may not be sufficiently active in a conventional orchard where  
334 pesticides have been sprayed for decades. The actual input is furthermore too low to fulfil the  
335 100 N units per hectare required by the trees to produce the yields considered.

336 Table 1. Climatic and production context of the area studied around Montpellier (France)  
337 (source: Pissonnier et al., 2016)

	SEF
Mean annual rainfall <sup>1</sup> (mm/year)	880
Mean annual temperature <sup>1</sup> (°C)	16.4

Production <sup>3</sup> (t)	79,500
% of national production <sup>3</sup>	4.6
Number of apple farms <sup>2</sup>	236
Apple surface area <sup>3</sup> (ha)	1,621
% of production sold in an AGC <sup>2</sup>	83
Average number of pesticide sprays per plot <sup>4</sup>	26

338 <sup>1</sup>(Météociel, 2013); <sup>2</sup>(Agreste, 2013); <sup>3</sup>(FranceAgriMer, 2014); <sup>4</sup>(Agreste, 2014)

### 339 3.2. *Selecting a farm and its objectives (steps 4-5)*

340 Based on the results of the diagnosis conducted in step 1, it was decided to exclude growers and  
341 cooperative technicians from the redesign process to avoid limitations on potential choices. A  
342 decision also was made to continue working with one of the farms surveyed for the diagnosis  
343 in order to maintain the focus on the reality of apple farm management. Apple production was  
344 the farm's only activity. The farm covered 36.5 hectares, and was located 40 kilometers outside  
345 Montpellier. Its spatial configuration is represented in SM1. The permanent workforce was  
346 composed of the farm head, his son, and two permanent salaried employees, who were each  
347 available 40 hours per week or 18 hours/hectare in total.

348 This farm was chosen because its resources and the farmer's objectives are representative of  
349 apple farms in South-East France. The farmer sought to produce high apple yields while  
350 respecting the quality criteria imposed by the cooperative's buyers. He did so by setting up well  
351 thought out production practices using a maximum of technical alternatives while limiting the  
352 risk of loss in quality and marketable yield. These alternative practices included birdhouses,  
353 hedges around orchards, and the use of biocontrol plant protection products such as granulosis  
354 virus and mating disruption against codling moth (*Cydia pomonella*).

355 The redesign objective was to assess the actual possibilities of evolution of a grower who is  
356 engaged in a long distribution channel and a non-organic production system, features  
357 characteristic of growers in the region under study. We decided to maintain the farmer's primary  
358 economic objective: maximizing the revenue from his apple production unit by respecting the  
359 criteria of his cooperative's buyers. Two scenarios then were designed that also included an  
360 environmental objective based on the integration of apples and sheep. The first, called  
361 "herbicide" ( $S_H$ ), aims for a minimum service of maintaining the grass cover on the orchard;  
362 the second, known as the "herbicide + pesticide" ( $S_{H+P}$ ), aims to reduce the use of synthetic  
363 inputs (plant treatment products) and agricultural machinery (mowers, boom sprayers), by  
364 making the most of the services provided by the sheep. These scenarios were compared to the  
365 "initial" scenario ( $S_I$ ) representing the actual configuration of the farm.

### 366 3.3. *Designing scenarios (step 6)*

#### 367 3.3.1. *Common decision rules*

368 Several common decision rules for the two scenarios were defined. The first set of rules was  
369 established in order to respect the economic objective: (i) do not exceed 200 sheep, so that the  
370 farm does not become specialized in livestock; (ii) do not uproot apple orchards to create  
371 grassland to avoid excessive loss of profits; (iii) do not have sheep grazing in the orchards  
372 during the periods when phytosanitary treatments are applied to avoid losses in fruit production  
373 on one hand, and animal health problems on the other. This leads the flock to graze in the  
374 orchard from the end of the harvest (September 15 for the earliest plots) up to the beginning of  
375 treatments (February 20), for a total of 158 days, and (iv) choose the Shropshire breed which  
376 grazes in orchards without attacking trees.

377 The second set of rules was made in order to meet the environmental objective regarding grass  
378 cover maintenance. The flock grazes the orchard from September to February, but grass grows

379 abundantly during the spring (Figure 3) when the sheep are off the orchard due to phytosanitary  
380 treatments. The flock therefore returns from time to time to graze the plots intensively as soon  
381 as a window of opportunity presents itself through several days without treatments. From May  
382 onwards, two passages can be envisioned before the next harvest due to the dryer weather and  
383 fewer treatments.

384 The third set of rules is linked to the basic needs of the flock that have to be fulfilled to reach  
385 minimum production: (i) no use of copper as it is harmful to animals (Hill, 1977); (ii) lambing  
386 concentration in March-April in accordance with the breed's natural reproduction period, (iii)  
387 sheep supplementation with salt blocks to fulfil their needs for minerals while avoiding attacks  
388 on trees, and (iv) access to water at a drinking point.

389 Given the soil and climate characteristics, each orchard plot must be allowed to rest for 35 days  
390 between two grazing passages to allow the grass to recover in quality and quantity. To respect  
391 this rest period, rotational grazing is set up, with at least 3 passages over the period between the  
392 harvest and the start of treatments to ensure the management of grass cover and respect of the  
393 environmental objective. The grazing units are defined according to the initial spatial  
394 configuration of the plots, knowing that the configuration of the orchard (irrigation, size) can  
395 remain identical because (i) the irrigation system is elevated and cannot be reached by the sheep;  
396 and (ii) the flock is off the orchard during the period of strong growth and fruit-forming.  
397 However, this configuration implies a relatively high loss rate of sheep (15%) to account for  
398 the difficulties involved in monitoring the most far flung plots (flights, thefts and deaths).

399 Several decision rules were set based on the socio-economic context of the farms: (i) a service  
400 provider shears the sheep and recovers the wool due to the technical complexity of the task and  
401 for the farmer to avoid having to assume the responsibility of marketing the wool for which  
402 there is no market in the region; (ii) during the spring while the sheep are off the orchard, a field  
403 near the farm can be rented to pasture the sheep since fields are available in the vicinity of the

404 farm following the uprooting of vineyards. The area available will remain limited to 5 hectares  
 405 due to the urban growth pressure in the region. Foddering is supplemented by hay during this  
 406 period to compensate for the limited rented area available and to respect the animals' needs; and  
 407 (iii) lambs are sold through direct sales channels due to the absence of a cooperative near the  
 408 farm and the existence of local demand. A nearby slaughterhouse proposes to slaughter and  
 409 package the meat, enabling the farmer to avoid additional equipment costs on the farm.

410 The total size of the flock was calculated based on Equation 1 considering that 200 sheep are  
 411 needed to graze one hectare in one day (vine reference). It consequently depends on the size of  
 412 the grazing units in the equation and the duration of time that the flock can graze on it. One to  
 413 two sheep are added to the total calculated to avoid under grazing. The total area of the farm  
 414 orchard is split into 1 to  $n$  blocks which gather the grazing units according to the spatial  
 415 configuration of the plots, and the management of both the orchard and the sheep flock.

416 
$$Batch_i = (\sum_{j=1}^n Surf_j^i \div n) \times 200 \div (Dur\_Graz \div (n - 1)) \quad (Eq.1)$$

417 Where:

418  $Batch_i$  = size of sheep batch for block  $i$

419  $Surf_j^i$  = surface of grazing unit  $j$  within block  $i$  ( $k$  grazing units)

420  $Dur\_Graz$  = duration of grazing on each grazing unit



421

422 Figure 3. Growth curve of grass on plains from March to October <sup>1</sup>

### 423 3.3.2. *The initial scenario S<sub>I</sub>*

424 Since S<sub>I</sub> consists only of the apple unit, the orchard component is considered to be a single,  
425 36.5-hectare block on which identical fruit tree management practices are implemented (SM2).  
426 The most time-consuming operation is the harvest, which represents 57% of the hours required  
427 for this production unit. The total TFI is 40, fungicides account for 45% of this total, insecticides  
428 for 32%. Labour represents the costliest item, ahead of fixed costs (57% and 26% respectively,  
429 SM3). With a yield of 60 ton/hectare and a selling price of €340/ton, the farm has a net margin  
430 of €5,120/hectare.

### 431 3.3.3. *Characterizing the sheep unit*

432 The costs and overtime associated with the introduction of the sheep unit are calculated in two  
433 phases: the installation phase, which requires investments in inputs and time, and the routine  
434 management phase, which requires regular and fixed expenses each year. The investments made  
435 for the installation phase, including the cost of labour, are subsequently recorded as depreciation  
436 charges over ten years in the routine management phase. The various operations related to the  
437 sheep unit are identified and their costs and labour time requirements are calculated and  
438 positioned monthly based on the references collected: watching over and caring for the flock;  
439 movement between grazing units, onto the pasture, and to the slaughterhouse; delivery of meat  
440 and sale on the farm; administration. The references used to calculate the labour time  
441 requirements are indicated in SM4. The costs and labour time requirements involved in setting  
442 up the S<sub>H</sub> and S<sub>H+P</sub> scenarios are listed in SM5 and SM6.

---

<sup>1</sup> French Livestock Institute, 2017. Bien conduire le pâturage pour optimiser la valorisation de l'herbe, Compilation of knowledge and references

443 Certain hypotheses are made regarding flock management: (i) a window without treatments  
444 exists starting from May that permits two grazing passages, (ii) the quantity and quality of the  
445 grass, as well as food supplements, are sufficient to meet the animals' physiological needs and  
446 deter attacks on trunks, leaves and fruit, (iii) the animals' docile behaviour enables these attacks  
447 to be avoided and limits fights, (iv) a sufficient amount of pasture fields are available around  
448 the farm, and (v) the grazing frequency (three passages from the harvest to the end of February  
449 and two from May to the next harvest) allows grass cover to be maintained on the rows but not  
450 completely on the inter-rows due to irrigation under canopy with sprinklers.

#### 451 *3.3.4. Specificities of the herbicide scenario $S_H$*

452  $S_H$  aims only to benefit from an orchard grass cover maintenance service provided by the sheep  
453 flock. According to testimonials and technical documents, a minimum of three grazing passages  
454 over the 158 days between the end of the harvest and the beginning of treatments are necessary  
455 to achieve this. A 52-day rotation is therefore established on the 36.5 hectares (one block).  
456 Thirty-three grazing units of one hectare each are defined by respecting the initial  
457 configurations of the plots. Each unit is bounded by a removable fence and is grazed for 1.5  
458 days (= 52/33). 150 sheep are required to respect this duration (Eq1). This configuration only  
459 allows shelters or plastic tunnels for the animals to be set up on the pasture field, not on the  
460 orchard.

461 Chemical weeding of the apple unit is eliminated, as well as rotary slashing to maintain the  
462 inter-row grass cover. However, rolling in May and August is added for inter-row management  
463 (2 hours/hectare each time), as the limits placed on grazing once the treatment period begins do  
464 not allow complete grass management. However, according to the testimonies, this low  
465 intensity grazing can only have a partial effect on protection through trampling/consumption of  
466 leaves and fruits, and this effect is considered to be null for this scenario.

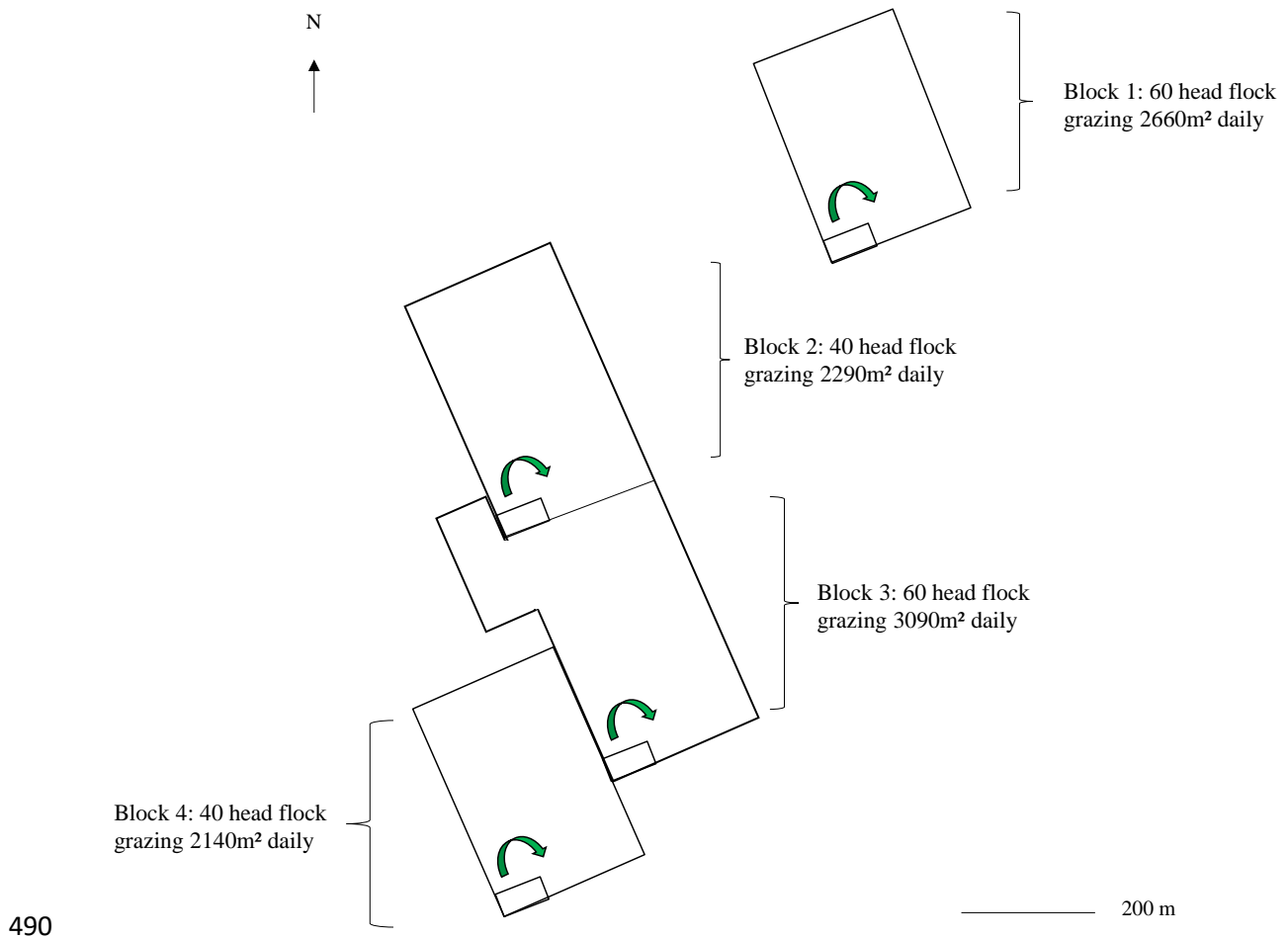
467 3.3.5. *Specificities of the herbicide + pesticide scenario  $S_{H+P}$*

468  $S_{H+P}$  aims to have the same effects as  $S_H$  in terms of maintenance of grass cover and to maximize  
469 the flock's impact on orchard protection by intensifying grazing through a higher stocking rate.  
470 This option allows a better trampling of fruits and leaves, with a possible effect in terms of  
471 protection, provided that the period that the sheep are present on the orchard coincides with pest  
472 development cycles (additional hypothesis).

473 In this scenario, the grazing units are 2000 to 3000 m<sup>2</sup> in size for more intensive trampling. The  
474 36.5 hectare area thus is composed of approximately 150 units. The 158 days of grazing  
475 between the harvest and the start of treatments does not permit several passes of the flock,  
476 reducing the effectiveness of the weed control. To address this constraint, the farm is divided  
477 into four blocks, each with its own batch of sheep. Each block has its own rotation, thereby  
478 enabling several passes (Figure 4). Isolated plots located northeast of the farm constitute Block  
479 1. Block 4 in the southwest is also determined naturally by the spatial configuration of the farm.  
480 The central part of the property is divided into two blocks to facilitate grazing: Block 2 contains  
481 all of the Pink Lady<sup>®</sup> plots, Block 3 the Granny and Golden plots.

482 Each block is divided into 35 units that are each grazed in one day, resulting in a 35-day rotation  
483 that respects the grass regrowth time requirements. The size of the units varies between 2290  
484 and 3090 m<sup>2</sup> depending on the configuration of the plots. The sizes of the batches are calculated  
485 using Equation 1, but the results are rounded up to the nearest ten above (for example, 32 to 40)  
486 to accentuate the effect of overgrazing, and to maximize the prophylactic effect against pests.  
487 The size of the batches thus varies from 40 to 60 sheep per block, and the entire flock has 200  
488 heads (Figure 4).

489



490

491 Figure 4. Organisation of rotational grazing between small areas on four blocks from the end  
 492 of the harvest up to the start of the first treatments

493 *3.4. Simulating the scenarios (step 7) and discussing the outputs (step 8)*

494 The three scenarios were simulated with CoHort and their outputs were compared on the three  
 495 main criteria provided by CoHort, i.e., pesticide use frequency (TFI), economic results (Figure  
 496 5) and labour balance (Table 2). The results were discussed between all of the researchers and  
 497 experts involved in the process.

498 The TFI reduction, which was the main driver of the redesign process, remains very low for  $S_H$   
 499 where the TFI is 39.25. The elimination of three herbicide treatments applied to 25% of the area  
 500 leads to a 2% reduction in relation to  $S_I$ . With four additional treatments saved,  $S_{H+P}$  achieves a  
 501 more interesting performance with a TFI of 35.25, resulting in a 12% reduction in TFI compared

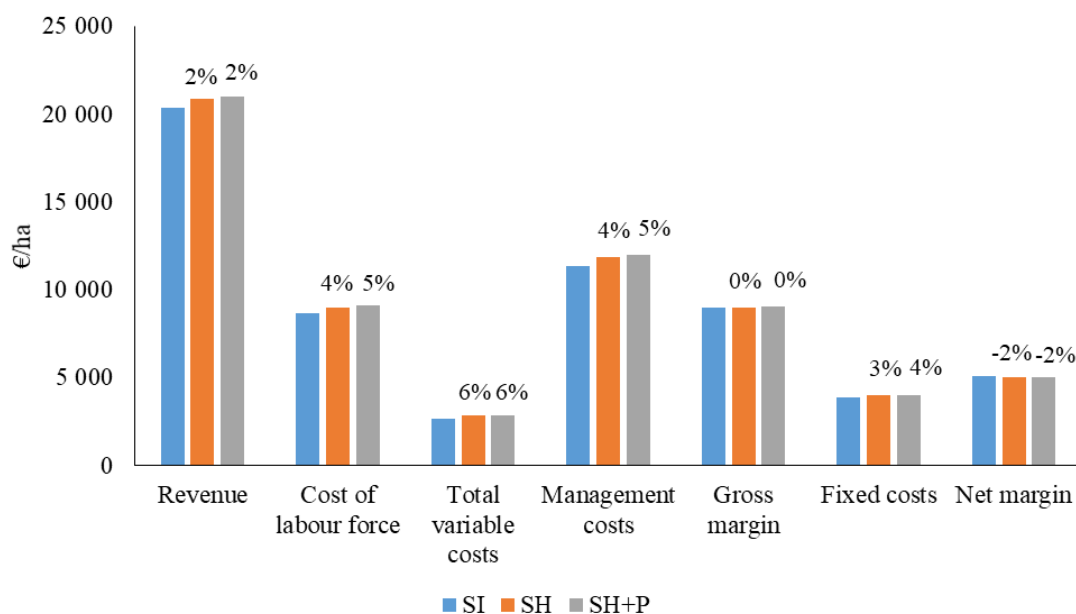
502 to  $S_I$ . However, reducing herbicides can have strong environmental impacts, since molecules  
503 from these kinds of phytosanitary products are highly represented in ground water (Le Bellec  
504 et al., 2015).

505 The introduction of a sheep unit on the farm does not appear to be an economically sound  
506 decision, even if the extra cost remains marginal compared to the costs of the apple unit  
507 (between €450/ha and €605/ha depending on the scenario for the sheep unit, compared to  
508 €15,280/ha for the apple unit). Indeed in both scenarios, the additional costs related to livestock  
509 are not totally compensated by the growth in revenue, nor by the benefits linked to the  
510 elimination of chemical weeding, and orchard health protection in the case of  $S_{H+P}$ . Meanwhile,  
511 the risks taken on the apple unit, under the hypothesis retained regarding the effects of the sheep  
512 unit on orchard management, could lead to reduced yields that would strongly impact the farm's  
513 overall economic performance. For example, a 10 ton/hectare decrease in yield in scenario  $S_{H+P}$ ,  
514 linked to less well managed protection against fungal diseases and poor climatic conditions,  
515 would lead to a 70% reduction in the net margin, jeopardizing the sustainability of the farm if  
516 it remains in the same marketing chain.

517 The increased workload required by the introduction of the sheep unit is low compared to the  
518 total requirements of the apple unit: respectively 937 hours and 1,379 hours for the sheep unit  
519 under  $S_H$  and  $S_{H+P}$  compared to 22,830 hours for the apple unit. However, this extra workload  
520 is not compensated by time saved through the elimination of certain treatments and grass  
521 management operations. The permanent workforce could absorb an increase in the demand for  
522 labour when this remains less than 10% compared to  $S_I$  (Table 2). However, given the total  
523 number of extra hours, the employment of a person half-time or even full-time over the year  
524 could be justified, especially for  $S_{H+P}$ . In such a farming context, this solution would face  
525 difficulties regarding the availability of labour both in terms of quantity and skills required. As  
526 the tasks are varied, this question may be considered in the light of the predispositions of the

527 seasonal and permanent employees already present on the farm and their affinity for these types  
 528 of activities.

529 This comparison shows that neither scenario can significantly improve all three indicators  
 530 selected. Based on that statement, further perspectives were discussed between all participants  
 531 (section 4).



532  
 533 Figure 5. Comparison of economic performances between the scenarios  
 534 Table 2. Variation of monthly workforce requirements of S<sub>H</sub> and S<sub>H+P</sub> compared to S<sub>I</sub> (%). In  
 535 red, the months where the requirement increases by 10%.

	J	F	M	A	M	J	J	A	S	O	N	D
S <sub>H</sub>	4	5	3	17	7	4	1	5	5	1	2	17
S <sub>H+P</sub>	10	9	-1	7	3	4	1	5	6	2	4	42

536

## 537 **4. Discussion**

538 The generic methodology proposed and illustrated in this study provides guidelines for  
539 researchers and experts aiming to assess the value and limits of radical ideas contributing to the  
540 transition towards biodiversity-based production systems at the farm level. Its two central  
541 components, i.e., participation of various stakeholders and quantitative evaluation based on a  
542 simulation tool at the farm scale, raise some issues discussed in the following sections.

### 543 *4.1. Designing radical scenarios at the farm level: dealing with hypothesis and references*

544 The design of radical scenarios at the farm level requires numerous hypotheses to be formulated  
545 and the use of diverse references adapted to the situation studied. Their nature and coherence  
546 guarantee the realism of the outputs of the simulations carried out in the subsequent phases of  
547 the design process. The agriculture-livestock integration scenarios studied here drew from four  
548 types of hypotheses and references. The first two refer to knowledge available on the  
549 biophysical and technical functioning of the system studied: (i) the nature of the physiological  
550 and climatic processes affecting both the sufficient growth of grass to feed the sheep and the  
551 links between grazing and treatments; and (ii) the consequences of farming practices on the  
552 maintenance of grass cover and orchard protection. This knowledge is sometimes available in  
553 the form of predictive models, for example concerning the assessment of grass growth (Martin  
554 et al., 2011), but their scope of validity is not necessarily transposable to the case studied. It is  
555 possible to call on the knowledge of experts (researchers, technicians, producers) whose  
556 empirical references are regarded as valid in the case studied, one example being the sheep  
557 stocking rate needed to maintain grass cover on one hectare. In the absence of knowledge  
558 considered valid, the use of a simulation tool like CoHort renders it possible to test the  
559 variability of simulation outputs with a range of values for certain input variables, for example  
560 with the crop yield taken into account. While obtaining these references seems critical for the  
561 question studied, for example, to assess the effects of grazing on the control of certain pests, a

562 process of experimentation, including or not the growers, also could be considered as an output  
563 of the redesign process (Le Bellec et al., 2012). The second two hypotheses refer to the specific  
564 features of the case studied, regarding (iii) its internal functioning, e.g., the availability of  
565 resources related to the livestock unit (rental fields, sheep, fodder), and (iv) its immediate  
566 environment, e.g., the existence of outlets for the sale of meat.

567 These hypotheses refer to discussions with local actors who are well familiar with their area's  
568 farms and territory and with whom the most plausible hypotheses are formulated (Martin et al.,  
569 2016). Whether the cases studied are real or totally virtual, the challenge for a scenario designer  
570 is to conceptualize the different elements that can interact within a farm and within the farm's  
571 environment in order to provide a coherent and realistic representation (Bood and Postma,  
572 1997). Producers already involved in the type of alternative system under consideration are  
573 important sources of information, which explains the value of methods used to identify them,  
574 such as innovation tracking (Salembier et al., 2016).

575 Due to the large number and heterogeneity of the references used in this design process applied  
576 to a radical scenario, caution is required with regard to the use of the simulation outputs. The  
577 study focuses more on trends than on results which are predictive. The approach is hence more  
578 a tool for reflection and exploration than a tool for decision-making vis-à-vis the actors able to  
579 intervene in the agroecologization of agriculture processes.

#### 580 *4.2. Involving farmers in the design and implementation of radical scenarios*

581 The involvement of the end-users in the redesign processes is generally beneficial and facilitates  
582 scenario adoption (Dogliotti et al., 2014; Lettl, 2007). Nonetheless, radical scenarios affecting  
583 the entire farm and its socio-technical environment are a special case since their design  
584 deliberately jumps over certain constraints that weigh on the decisions actually taken by  
585 producers. However, once such scenarios are designed and simulated, they serve to provide the

586 potential end-users, i.e., the farmers, both quantitative elements, such as ranges of values, and  
587 qualitative interactions between farm components to strategically explore radical alternatives.  
588 For instance, the results of the orchard-sheep combination studied here show that this radical  
589 alternative only seems conceivable in certain contexts, namely (i) when growers are really  
590 motivated by livestock farming, or (ii) the combination is accompanied by a shift in marketing  
591 strategy towards short distribution channels with possible certification in organic farming,  
592 which could compensate for the risk taken *via* higher prices and lower visual quality constraints  
593 (Brewer et al., 2004), or even (iii) there are changes in regulations governing plant protection  
594 products, including herbicides (Storck et al., 2017).

595 The radical feature therefore no longer only concerns the farm's internal organization, but also  
596 its overall strategy. This strategic thinking requires support in terms of advice that integrates  
597 the different dimensions of the farm, both in terms of production activities and performance  
598 (Faure and Compagnone, 2011). The example studied in this article shows how difficult it is to  
599 carry out this exercise, one that assumes the support of consultants with expertise in the crop  
600 and animal productions concerned, covering their technical, economic and environmental  
601 components (Le Gal et al., 2013). These difficulties undoubtedly explain why redesign is not  
602 the first option chosen by farmers and advisory structures to respond to the challenges posed  
603 by agroecological transition. Their choices more naturally turn to the efficiency and substitution  
604 components of Hill and MacRae's framework (Aulagnier and Goulet, 2017), which require a  
605 better use of synthetic inputs (spray during optimal climatic conditions, vegetative or pest state),  
606 or a substitution of synthetic inputs by 'natural' ones.

#### 607 *4.3. Beyond the farm level?*

608 The simulations made using CoHort enabled the assessment of the close integration of an apple  
609 unit and a sheep unit within the same farm. The results of this specific example confirm the  
610 difficulty of integrating livestock units on farms specialized in plant production. However, there

611 are alternatives where farmers could still benefit from the ecological processes, but limit the  
612 consequences on their farms. For example, another potential path consists of organizing  
613 exchanges at the territory level between farms specializing in a certain types of production  
614 (Martin *et al.*, 2016). On fruit tree farms, these exchanges involve bringing in an outside flock  
615 at certain key periods: spring for grass growth, autumn for scab (*Venturia inaequalis*) (IRAEE,  
616 2018). This type of system assumes, however, that there are livestock farms in close proximity  
617 to the fruit tree farms, and that arrangements can be made to enable these exchanges to operate.

618 Different types of collaborations and their constraints and benefits are analyzed in the literature,  
619 including: manure – straw exchanges between organic farms in Denmark (Asai and Langer,  
620 2014); integrations within and among farms in North America (Russelle et al., 2007); and  
621 collaborative management on forested landscapes (Gass et al., 2009). However, designing such  
622 systems at a regional scale, involving a diversity of actors, strategies and power asymmetries,  
623 is difficult (Barnaud and Van Paassen, 2013). Studies on the design of such systems are rare  
624 and tools and methodologies are needed (Martin et al., 2016). The approach we developed and  
625 the simulation tool CoHort could participate in these methodologies, since adaptations at the  
626 farm level will still be necessary to enhance coordination and exchanges between farmers. For  
627 example, in synergic collaborations for crop-livestock integration, farmers adapt their crop  
628 rotation to animals' needs whereas breeders process animal feces and bring it to growers  
629 (Watson et al., 2019). Combined with similar simulation tools focused on crop-livestock  
630 farming systems (Le Gal et al., 2013), CoHort could then contribute by assessing the impacts  
631 of such evolutions at the farm level, but also at the territory level by aggregating simulation  
632 outputs.

### 633 **Conclusion**

634 The redesign component of agroecological transition involves reflection on the biodiversity-  
635 based reconfiguration of production systems at the farm and territorial levels. The design and

636 simulation of “radical” scenarios can effectively nourish this reflection as they break away from  
637 the actual realities experienced by most farmers. The eight-step approach described and  
638 illustrated here, one based on the case of a farm associating fruit tree crops and livestock,  
639 proposes a way to organize this process from the diagnosis of the initial production context to  
640 the evaluation of the radical ideas explored. By using a simulation tool, the results obtained  
641 make it possible to discuss such ideas at the farm level, both from a quantitative perspective by  
642 calculating economic, environmental and organizational indicators, and a qualitative one by  
643 discussing the conditions required for their implementation.

644 In the absence of scientific research on certain hitherto unaddressed technical issues, the wealth  
645 of knowledge and references used in such work are often empirical because they are drawn  
646 from farmers' experiences. One outcome therefore is a better understanding of the interest of  
647 assessing the biophysical consequences of certain innovative practices, for example on yields.  
648 By putting these practices in the context of farms and territories, a second outcome is to nourish  
649 debates between farmers, researchers and technicians on the merits of such configurations on  
650 this type of farm. This redesign approach can potentially be applied to many topics, ranging  
651 from the coherent combination of agroecological practices to futuristic scenarios involving the  
652 mechanization of tasks via the use of robots.

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