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# 1 **Collective design of innovative agroecological cropping systems** 2 **for the industrial vegetable sector**

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10

## 11 **ABSTRACT**

### 12 1. Context

13 There is an urgent need to reduce the use of phytosanitary products in industrial vegetables  
14 due to environmental and health concerns. However, as in many industrial sectors,  
15 vegetables production is characterised by strong constraints related to the expectations of  
16 consumers, the profitability of distributors and the processing steps of industrial companies.  
17 These constraints impact farming systems through the elaboration of production contracts  
18 that hamper innovation and reduce farmers' latitude to evolve towards agroecology.

### 19 2. Objective

20 This study was initiated by a French distributor of frozen products, and aimed to create  
21 innovative agroecological cropping systems by circumventing lock-ins of the sector thanks  
22 to a co-design methodology.

### 23 3. Methods

24 An existing methodology of innovative cropping systems design for fresh vegetable crops  
25 was adapted to the context of industrial production, considering the 3-year deadline granted  
26 to the project. Four farmers were involved, who were part of a working group consisting of a  
27 distributor, a processing company, a cooperative and a research team, all involved in the  
28 production of frozen vegetables. Four cropping systems were designed, consisting in  
29 combinations of agroecological farming practices, and tested on farm for two years.

### 30 4. Results and conclusions

31 Farmers reduced their Treatment Frequency Index by 15% on average, thanks to the  
32 combination of a wide range of agroecological farming practices. A multi-criteria analysis  
33 showed that there was no clear improvement in overall cropping system sustainability, due to  
34 economic weaknesses. Although these results were somewhat disappointing, especially with

35 respect to the expectations of public policies, they represent a significant progress given the  
36 difficulty to reduce the use of chemical pesticides in industrial systems. Farmers underlined  
37 the importance of economic security but were nevertheless highly motivated to continue the  
38 transformation of their systems, and the working group collectively approved the  
39 methodology. Four methodological aspects are discussed, identified as key elements for  
40 consideration in this type of study: farm system scale, collective work, farm system flexibility,  
41 and farm system uniqueness. Based on these principles, the working group decided to  
42 extend the study to a larger scale, with the aim of recruiting more farmers from the sector.

#### 43 5. Significance

44 This study shows that making cropping systems with industrial vegetables evolve toward  
45 agroecology is possible thanks to a co-design methodology. In the long term, such initiatives  
46 could support the transition of the whole agrifood system toward the production of healthier  
47 products, reducing negative environmental impacts of cropping systems.

48

#### 49 **KEYWORDS**

50 Farming system ; cropping systems design ; industrial vegetables ; agroecology ; innovation ;  
51 collective approach

52

#### 53 **HIGHLIGHTS**

- 54 • Industrial vegetables sector is characterised by intensive practices and strong  
55 constraints related to production, transformation and marketing.
- 56 • This study aimed to create innovative cropping systems by overcoming sectorial lock-  
57 ins thanks to an adapted co-design methodology.
- 58 • Four innovative systems based on combinations of agroecological practices were  
59 designed collectively and experimented by farmers.
- 60 • Despite fragile economic results, the working group was satisfied, approved the  
61 methodology and decided to extend the study to a larger scale.
- 62 • Such initiatives could support the transition of the whole agrifood system toward the  
63 production of healthier products in a more sustainable way.

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## 71 INTRODUCTION

72

73 In France, 900,000 tons of vegetables are produced each year for the industrial  
74 market, and occupy about 70,000 ha (Bernardin, 2018). This sector is usually associated  
75 with big farms (about 130 ha) with a diverse range of activities, such as livestock farming and  
76 cereal cropping (Pierron, 2016). Vegetable crops are characterised by a large diversity of  
77 cultivated species, susceptible to many pests and diseases. To control pests and guarantee  
78 the quality and yield of vegetable productions, farmers use a significant amount of pesticides,  
79 potentially damaging agroecosystems and the services they can provide (Gregory et al.,  
80 2002; Pimentel and Lehman, 1993). Health issues related to pesticides are also increasingly  
81 regarded as a major societal problem, especially for consumers (Boccaletti and Nardella,  
82 2000; Carvalho, 2017). Indeed, surveys in France found that chemical treatments on crops  
83 and their residues in food are one of the main concerns about food consumption (Hebel,  
84 2008). In order to make progress on these issues, an increasing number of political decisions  
85 have gradually been made to ban the use of dangerous phytosanitary products. For industrial  
86 vegetables growers, these regulations are added to a large set of specifications (Henson and  
87 Humphrey, 2012) ensuring downstream processing, sanitary and visual quality of products,  
88 as well as yields, which are generally incompatible with a reduction in pesticide use (Lamine,  
89 2011). In this context, a consultation between the different stakeholders in the industrial  
90 vegetable sector is clearly required to develop a consistent and sustainable strategy to  
91 reduce pesticide use and revalue products (Duru and Therond, 2015).

92 The main goal of agroecology is to manage agro-ecosystems in a sustainable way  
93 balancing their environmental, economic and social aspects (Altieri, 1989). Agroecological  
94 farming practices can be defined as methods contributing to the sustainability of agro-  
95 ecosystems based on a diversity of ecological processes (Wezel et al., 2014). Farmers  
96 increasingly adopt these practices to adapt their farm systems to environmental problems,  
97 health concerns and political constraints (Méndez et al., 2012). As described in the ESR  
98 (Efficiency-Substitution-Redesign) framework (Chantre and Cardona, 2014; Hill and MacRae,  
99 1995; Wezel et al., 2014), this appropriation can be achieved with different transition  
100 strategies. The complete redesign of farm systems is the most advanced approach, since it  
101 involves the design and the adoption of new combinations of innovative and coherent  
102 farming practices (Chantre and Cardona, 2014). It can require technically difficult and risky  
103 practices (*e.g.* modification of crop rotation, direct seeding into living cover crops, ...) and is  
104 usually based on a long and non-linear process (Lamine, 2011). However, it can help  
105 creating robust and transformative systems answering the ambitious expectations of modern  
106 society (Pretty, 2018).

107           The design of innovative cropping systems developed strongly in France during the  
108 last decade, because it was identified as a promising approach to make agroecosystems  
109 more sustainable (Meynard et al., 2012; Prost et al., 2017). It is mainly characterised by a  
110 collective dimension, the aim being to design new systems based on established and  
111 empirical knowledge of various stakeholders (farmers, researchers, advisers, territorial  
112 players, etc.) (Lacombe et al., 2018; Lançon et al., 2008; Reau and Doré, 2008). Numerous  
113 initiatives have emerged worldwide, in developing countries but also in intensive production  
114 regions, for a diversity of crops, sectors, farming contexts, and purposes (Berrueta et al.,  
115 2021; Debaeke et al., 2009; Dogliotti et al., 2014; Falconnier et al., 2017; Lançon et al., 2007;  
116 Le Bellec et al., 2012; Lefèvre et al., 2014; Reckling et al., 2020). Modelling has been used to  
117 explore innovative management strategies at the farm level (Olesen et al., 2006; Sadras et  
118 al., 2003; Zingore et al., 2009). A lot of methodologies have been formulated, and some  
119 authors proposed syntheses and classifications of design studies (Le Gal et al., 2011; Martin  
120 et al., 2013). In France, guidelines were written (Aubertot et al., 2011; Barbier et al., 2011;  
121 Bruchon et al., 2015; Laget et al., 2015; Launais et al., 2014; Meynard et al., 2012) to help  
122 farmers and advisers implement complete and collective redesign of cropping systems,  
123 targeting the reduction of pesticide use. Numerous field studies were conducted under these  
124 guidelines, and have made significant contributions to solve the challenges of French  
125 modern agriculture. A good example is the DEPHY network, a French network funded by the  
126 Ministry of Agriculture and Food and dedicated to the trial and assessment of low inputs  
127 cropping systems (Eckert et al., 2018; Lechenet et al., 2017). However, despite the large  
128 diversity of design studies, few initiatives have concerned the vegetable sector, and fewer  
129 still the industrial vegetable sector, probably because of the strong constraints and  
130 regulations previously mentioned.

131           Reducing the use of pesticides in agriculture is an ambitious challenge, encouraged  
132 in France since 2008 by the Ecophyto plan (Lamichhane et al., 2019; Ministry of Ecological  
133 and Solidarity Transition, 2018). However, some major locks have progressively been  
134 identified, responsible for the disappointing results observed by involved stakeholders  
135 (Guichard et al., 2017). Among these locks, the lack of involvement of the whole agrifood  
136 system was pointed out as a big concern (Lamine, 2011). In a quite recent study, Meynard et  
137 al. (2017) argued for the design of coupled innovations, *i.e.* improvements jointly conducted  
138 by downstream and upstream stakeholders of agrifood systems. Farm system design is  
139 indeed usually driven by upstream actors (farmers, technical advisers), considering  
140 constraints and specifications from downstream actors (related to processing, distribution,  
141 preparation and consumption of food) that restrict innovation. In order to reach sustainability,  
142 all the components of the agrifood systems should however require a huge need for  
143 innovation, so working collectively seems an essential approach (Duru and Therond, 2015;

144 Gliessman, 2014; Lamprinopoulou et al., 2014; Meynard et al., 2017). The literature about  
145 socio-technical systems shows that in a locked-in system, as is the case for the industrial  
146 vegetable sector, radical innovations can emerge in “innovation niches”, *i.e.* in alternative  
147 socio-technical systems composed of outsider actors that can emerge from a collective  
148 design process (Geels, 2005; Kemp et al., 1998; Meynard et al., 2017).

149 The aim of this study was to apply, adapt and evaluate the methodology of innovative  
150 cropping systems design for the industrial vegetable sector, from a guideline written for fresh  
151 vegetable crops (Launais et al., 2014). It is an original approach, since the work was  
152 collaboratively conducted by five major stakeholders in the sector, and especially a  
153 distributor and a processing company, characterised by different sets of constraints.  
154 Innovative cropping systems were co-designed and experimented in the west of France, with  
155 two main goals: reduce the environmental effects of farming practices and anticipate the  
156 progressive banning of phytosanitary products. The study was directly conducted in a context  
157 of vegetable production, with four pilot farmers.

158

## 159 **METHODS**

160

### 161 Study area

162 The study was carried out from 2015 to 2018 in Brittany, which is one of the major  
163 French regions where industrial vegetables are produced, with 33% of the total French  
164 cultivated area (Bernardin, 2018). In Europe, the sector is driven by a small number of large  
165 processing companies with similar agronomical, industrial and economic functioning. The  
166 results can consequently be transposed to some extent to the French and European sector  
167 at large. In Brittany, a large part of the region area is dedicated to farming, with a majority of  
168 crop-livestock farms with grassland, corn and wheat (Agreste, 2016). Vegetables, mainly  
169 green beans, peas, spinach and carrots, occupy nearly 3% of the cultivated area (Bernardin,  
170 2018).

171

### 172 Background of the study

173 The study was initiated in 2015 by the company Picard, a distributor of frozen food  
174 products. Based on a life cycle assessment conducted on some of their vegetable-based  
175 products, this company realized that the production phase (in fields) was the most damaging  
176 for environment. They asked the processing company Ardo and the French National  
177 Research Institute for Agriculture, Alimentation and Environment (INRAE) to build a collective  
178 project to address this issue. An initial three-year working step was defined and  
179 contractualised between the three collaborators. The overall goal was to collectively design  
180 and experiment innovative cropping systems to reduce the environmental effects of farming

181 practices and anticipate the progressive ban of phytosanitary products. Collaborators  
182 decided to work directly in the production context (instead of working in an experimental  
183 platform), first testing the method with a pilot group of four farmers. It was assumed that  
184 enough knowledge was available to design coherent systems, and that these systems  
185 needed to be tested directly by farmers to meet Picard expectations and project objectives in  
186 the allotted time of three years.

187

### 188 Collaborator's roles and constraints

189 Five major stakeholders in the industrial vegetables sector were involved in the study:

190 1. Picard is the French leader in the distribution of frozen food products, with a 19% market  
191 share. They have about 1,000 shops in France, where more than 70 types of vegetable  
192 products are sold every day. As all distributors, Picard needs to meet health standards and  
193 customers' expectations. This means offering vegetables alone or mixed in recipes,  
194 respecting the authorised threshold of physico-chemical and biological contaminants, and  
195 presenting a visual aspect and a taste adapted to consumer preferences. It can also mean  
196 proposing products that reflect social trends, for instance about health considerations.  
197 Finally, Picard needs to offer these products on a regular basis, with a consistent quality.  
198 During the project, Picard was represented by two staff members belonging to either the  
199 Sustainable Development department or the Quality department.

200 2. Ardo is a major European processing group specialised in the deep-freezing of  
201 vegetables, fruits and aromatic plants. The company is established in nine countries  
202 including France, and one of the factories is located in Brittany. They collect harvested  
203 vegetables and they transform, freeze and pack them. Picard is one of their clients. Ardo and  
204 Picard are linked by contracts that specify Picard expectations about products quality and  
205 quantity, as previously described. In order to meet these specifications, Ardo needs to collect  
206 the right amount of vegetables at the right time, matching quality criteria and suitable for the  
207 different processing steps, *i.e.* sorting, cleaning, cooking, freezing and packaging. This  
208 means collecting vegetable batches without too many residues of foreign plants or animals,  
209 with a given size, a given texture, a given shape, etc. During the project, Ardo was  
210 represented by two staff members belonging to the sales and supply chain department (the  
211 director and his deputy) of the Britannic factory.

212 3. Four farmers were involved in the study, forming a pilot group. They are all members of  
213 the farmer cooperative Triskalia, and more precisely of the industrial vegetable subgroup.  
214 Farmers were solicited by Ardo, and took part to the project on a voluntary basis. A contract  
215 was signed between each farmer, Ardo and Picard, specifying farmers had to devote time to  
216 the project and that they were financially supported for the experiment. A budget was indeed  
217 defined at the beginning of the project to cover additional expenses and compensate

218 farmers' income in case of yield loss. The main characteristics of their farms are given in  
 219 Table 1. Their vegetable crops are included in quite long cropping sequences (6-7 years)  
 220 with other field crops (cereals, oilseed rape, buckwheat, etc). They however had different  
 221 production and cropping systems, different initial levels of involvement in agroecology, and  
 222 different priorities for their farms. This diversity is a key point of the study because it  
 223 contributes to the representativeness of the pilot group. All industrial vegetable crops are  
 224 grown under contracts, which impose the specifications, defined by the buyers (mainly Ardo  
 225 in the pilot group), that the farmers must meet. This contractual system is used by all  
 226 processing companies and allows configuring the raw material (vegetables here) according  
 227 to the needs of the sectors. For farmers, it means respecting a precise crop management  
 228 planning, including sowing (date and variety), fertilisation, pests management and harvesting  
 229 (date and yield). As long as specifications are respected, farmers benefit from a guaranteed  
 230 price for their vegetables.

231 4. Triskalia is one of the main farmer cooperatives in Brittany, with 16,000 members and  
 232 4,800 employees. It is organised in different subgroups depending on farm products. The  
 233 industrial vegetable subgroup includes 600 farmers. Ardo is one of their clients. Triskalia was  
 234 not part of the project creation and management but it was associated to the design of  
 235 cropping systems and to the experimentation phase. For vegetables production, farmers  
 236 usually rely on advices provided by technical advisers because it helps them following the  
 237 specifications imposed by industrial companies. Persons involved were the industrial  
 238 vegetable subgroup manager and the technical advisers of each farmer (one for vegetable  
 239 crops and one for other crops).

240 5. The National Research Institute for Agriculture, Alimentation and Environment (INRAE) is  
 241 a major French scientific establishment. Agroecology and farm transition toward sustainable  
 242 systems are part of its numerous research topics. For this project, INRAE's role was to  
 243 propose and manage an original approach to help farmers change their cropping systems.  
 244 INRAE also provided a scientific evaluation to decision-making. During the study, INRAE was  
 245 represented by two researchers specialised in cropping system design.

246

247 *Table 1. Main characteristics of the farms involved in the project.*

	Farm A	Farm B	Farm C	Farm D
<b>Total cultivated area</b>	111ha	110ha	93ha	94ha
<b>Vegetable area</b>	20ha	40ha	20ha	10ha
<b>Activities</b>	<ul style="list-style-type: none"> <li>• Industrial vegetables</li> <li>• Cereals</li> <li>• Livestock farming (ducks, cows)</li> </ul>	<ul style="list-style-type: none"> <li>• Industrial vegetables</li> <li>• Cereals</li> <li>• Wheat, clover and ryegrass seeds</li> <li>• Farming work for</li> </ul>	<ul style="list-style-type: none"> <li>• Industrial vegetables</li> <li>• Cereals</li> <li>• Potato and ryegrass seeds</li> <li>• Farm tourism</li> </ul>	<ul style="list-style-type: none"> <li>• Industrial vegetables</li> <li>• Cereals</li> <li>• Livestock farming (chickens, cows)</li> </ul>



	neighbors			
<b>Cultivated vegetables</b>	<ul style="list-style-type: none"> <li>• Peas</li> <li>• Green beans</li> </ul>	<ul style="list-style-type: none"> <li>• Peas</li> <li>• Green beans</li> <li>• Winter spinach</li> </ul>	<ul style="list-style-type: none"> <li>• Peas</li> <li>• Green beans</li> </ul>	<ul style="list-style-type: none"> <li>• Spring spinach</li> <li>• Carrots</li> <li>• Broccoli</li> <li>• Cauliflowers</li> </ul>
<b>Other cultivated species</b>	<ul style="list-style-type: none"> <li>• Winter wheat</li> <li>• Winter barley</li> <li>• Grain corn</li> <li>• Oilseed rape</li> <li>• Faba bean</li> <li>• Buckwheat</li> </ul>	<ul style="list-style-type: none"> <li>• Winter wheat</li> <li>• Ryegrass</li> <li>• Clover</li> </ul>	<ul style="list-style-type: none"> <li>• Winter wheat</li> <li>• Winter barley</li> <li>• Triticale</li> <li>• Ryegrass</li> <li>• Potatoes</li> </ul>	<ul style="list-style-type: none"> <li>• Winter wheat</li> <li>• Corn silage</li> </ul>
<b>Commitment to agroecology</b>	High	Medium	Medium	Low
<b>Main agronomical problematics</b>	<ul style="list-style-type: none"> <li>• weeds and diseases control in vegetable crops</li> <li>• aphids and leaf weevils control in peas</li> </ul>	<ul style="list-style-type: none"> <li>• weeds control in spinach, wheat and ryegrass</li> <li>• diseases control in green beans</li> </ul>	<ul style="list-style-type: none"> <li>• volunteer potato</li> <li>• click beetles control in potatoes</li> </ul>	<ul style="list-style-type: none"> <li>• weeds control in carrots</li> <li>• selection of suitable cover crops</li> </ul>
<b>Main priorities of the farmer</b>	<ul style="list-style-type: none"> <li>• Conservation farming</li> <li>• New technologies</li> </ul>	<ul style="list-style-type: none"> <li>• Precision farming</li> <li>• Direct seeding into cover crops</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of working time</li> <li>• Concrete, local and social projects</li> </ul>	<ul style="list-style-type: none"> <li>• Technical progress</li> <li>• Cost efficiency</li> </ul>

248

## 249 Study approach

250 The design and testing of the innovative cropping systems for the farmer pilot group was  
 251 based on a framework proposed by Launais et al. (2014). This guide was written to help  
 252 stakeholders from the fresh vegetables sector to design cropping systems using less  
 253 pesticides. Four working steps are proposed: the diagnostic of the existing system, the  
 254 design of an innovative system, the *ex-ante* analysis of the innovative system, and the  
 255 identification of needed conditions to implement the innovative system. This methodology  
 256 was adapted in order to work in the context of industrial vegetables production and to answer  
 257 Picard request in the allotted time (i.e. including the experimentation and the analysis of  
 258 implemented systems within three years).

259

## 260 **Description of initial cropping systems**

261 The study began with a complete and precise description of each farmer's initial  
 262 cropping system. If a farmer had several cropping systems with vegetables, only the main  
 263 one (*i.e.* the most represented in terms of area) was considered. Information was collected  
 264 during interviews which purposes were to define and clearly understand the starting point for  
 265 each farmer, encourage them to review the functioning of their system and identify its  
 266 strengths and weaknesses. Each interview lasted half a day, took place on the farm and was  
 267 organised in two parts:

- 268 - The overall functioning of the farm: establishment date, activities, cultivated species,  
269 abandoned species, cultivated area, number and size of fields, spatial distribution, main soil  
270 characteristics, weather conditions, agricultural equipment, manpower, main landscape  
271 characteristics, relationships with neighbouring and economic partners, contractual  
272 commitments, priorities, agronomical problematics, overall satisfaction;
- 273 - The precise technical operations carried out for each crop of the studied cropping systems:  
274 intercropping (cover crop, sowing and destruction dates), tillage (number of interventions, soil  
275 preparation tools), seeding (date, variety, sowing density, seed treatments), fertilisation (date  
276 and quantity of each organic and mineral product), pest management (target species, date  
277 and quantity of pesticides applications, other management strategies), irrigation (amount of  
278 water, equipment), harvesting (date, average yields).

279

### 280 ***Collective conception of innovative cropping systems***

281 Innovative cropping systems were designed during workshops organised in 2016.  
282 Before workshops, the project leaders (Picard, Ardo, INRAE) selected a set of aims which  
283 constituted a guiding thread for designing the innovative cropping systems:

- 284 - Reduce the use of pesticides as much as possible;
- 285 - Adjust fertiliser inputs to crop needs;
- 286 - Introduce a large diversity of alternative agroecological farming practices, based on  
287 scientific studies and previous empirical trials by farmers.

288 For each innovative system, these technical aims were supplemented with the expectations  
289 of the farmer concerned. Economical and social parameters were not directly included in the  
290 workshops' aims, but were always kept in mind during discussions (for instance when a  
291 choice had to be made between two practices), in order to design sustainable cropping  
292 systems. Economical and social characteristics of the systems were assessed in the  
293 evaluation step.

294 Each workshop was one day long and was located on the farm of the farmer concerned. The  
295 aim was to completely redesign the initial cropping system, *i.e.* the crop sequence and  
296 technical operations carried out on each crop, following the expectations and ideas of all  
297 participants. There were 12 to 14 participants in each workshop: members of the central  
298 working group (Ardo, Picard, INRAE and the four farmers) and specific guests (one animator,  
299 one or two farmer technical advisers, and one or two agronomy experts specialised in  
300 vegetables). This configuration allowed Ardo, Picard and the focus farmer to express their  
301 expectations and the whole group to come up with a maximum of new ideas. The four  
302 farmers were present during all the workshops, so each of them was involved in the design  
303 of his own cropping system and in the design of other farmers cropping systems.

304 Each workshop was organised in five parts:

- 305 1. The farmer presented a detailed summary of his current cropping system;
- 306 2. The aims for the new innovative cropping system were specified. These aims were
- 307 determined collectively since the new system must meet everybody's expectations;
- 308 3. New ideas for the innovative system were proposed (new crop sequences, new farming
- 309 practices). During this step, all participants (except the farmer) wrote their ideas on post-it
- 310 notes then shared with the group;
- 311 4. The best ideas were chosen to create a consistent and operational innovative system,
- 312 based on the combination of compatible farming practices. Once again, these decisions were
- 313 made collectively, with the exception of the farmer concerned who just observed the group;
- 314 5. A collective synthesis and feedback was given from the farmer concerned on his new
- 315 cropping system.

316 After each workshop, a decision sketch was prepared, which is a comprehensive

317 representation of the aims and the management strategies relative to a cropping system

318 (Schaub et al., 2016). It helps to visualise the overall consistency of a system (combination of

319 farming practices) and provides a good tool for discussion and management.

320 In 2017, an additional half-day workshop was organised with each farmer. The aim was to

321 collectively take stock of the first year and get an update on each innovative cropping

322 system, based on farmers' observations.

323 In 2018, farmers were met individually to take stock of the second year.

324

### 325 ***Testing the innovative cropping systems***

326 The four farmers tested their own innovative systems in 2016, 2017 and 2018. The

327 aim was to set up the innovative systems entirely from the start, *i.e.* to make as many of the

328 designed changes as soon as possible and on as many fields as possible in each farm.

329 Technical advisers from the cooperative and a researcher from INRAE guided the farmers to

330 i) help them anticipate the specific needs (*e.g.*, mechanical weeding equipment), ii) remind

331 them regularly of the necessary changes to be made, iii) observe the consequences of these

332 modifications.

333

### 334 ***Assessing the sustainability of the innovative cropping systems***

335 Three complementary tools were used to evaluate the sustainability of the cropping

336 systems. Each tool was used to compare i) initial cropping systems, ii) theoretical cropping

337 systems designed during the workshops, and iii) cropping systems actually implemented in

338 2016, 2017 and 2018.

- 339 1. The number of agroecological farming practices provided a first evaluation of cropping
- 340 system sustainability. Like Wezel et al. (2014), we considered agroecological farming
- 341 practices in the broad sense of the word, *i.e.* all farming practices "*aiming to produce*

342 *significant amounts of food, which valorise in the best way ecological processes and*  
343 *ecosystem services in integrating them as fundamental elements in the development of the*  
344 *practices, and not simply relying on ordinary techniques, such as chemical fertiliser and*  
345 *synthetic pesticide application or technological solutions, such as genetically modified*  
346 *organisms*". We considered that one farming practice is one action carried out by a farmer on  
347 a crop. Consequently, if a farmer made mechanical weeding on two different crops of its  
348 cropping systems, it was counted as two different practices. After each trial, farmers were  
349 asked about tested and non-tested farming practices. Reasons of non-inclusion of some  
350 farming practices identified during the design phase were collected and classified. Farming  
351 practices enumeration does not match with the systemic way of thinking associated with a  
352 co-design approach, but it provides quantitative data, useful to evaluate cropping systems  
353 and exchange with farmers.

354 2. The Treatment Frequency Index (TFI) is an indicator used to evaluate the intensity of  
355 phytosanitary products use by farmers. It is calculated as follows:

356

$$357 \quad TFI = \sum \frac{\text{dose applied}}{\text{recommended dose}} \times \frac{\text{treated area}}{\text{field area}}$$

358

359 TFI is widely used by farmers and agronomists since it is easy to calculate and operational at  
360 different levels: it can be calculated at different scales (field, crop, cropping system, farming  
361 sector) and for diverse pesticide categories (herbicides, insecticides, fungicides). In this  
362 study, mean annual TFI were calculated for each cropping system, distinguishing between  
363 classic pesticides and products registered as "NODU vert Biocontrôle" (called "biocontrol  
364 products" in the article). This French certification describes products of natural origin used for  
365 the control of pests (French ministry of agriculture agribusiness and forestry, 2015a). This  
366 distinction was made because using a biocontrol product was considered as an  
367 agroecological farming practice.

368 3. Multi-criteria analyses encompass numerous approaches used to combine environmental,  
369 socio-political and economical information in tools helping stakeholders to understand  
370 multifactorial situations and make decisions (Huang et al., 2011). In this study, we used  
371 DEXiPM-FV, a hierarchical qualitative and multi-criteria model, developed to analyse the  
372 sustainability of field vegetable cropping systems (Estorgues et al., 2017; Pelzer et al., 2012).  
373 This model allows *ex-ante* analyses on virtual cropping systems not yet tested by farmers,  
374 with qualitative data. Since the *ex-post* version of the model to analyse actual cropping  
375 systems with quantitative data has not yet been developed, we used the existing tool to  
376 compare all cropping systems in the study using qualitative data only. For each cropping  
377 system, 87 indicators were included in the model, chosen with the help of the farmers pilot

378 group. Analyses were conducted on IZI-EVAL 2.0.1, an interface created to use DEXi  
379 models.

380

## 381 RESULTS

382

### 383 Implementation of agroecological farming practices

384 During the study, the four farmers mobilised 21 types of agroecological farming  
385 practices, which were classified into seven categories (Table 2). This large diversity of  
386 farming practices included modifications of crop sequences, the main technical operations  
387 carried out on crops (intercropping, tillage, seeding, fertilisation, pest management), and  
388 more indirect actions related to biodiversity observation and enhancement. The four farmers  
389 implemented the innovative cropping systems on their whole farms, except for fields  
390 occupied with permanent grasslands or unsuitable for some practices (for instance fields with  
391 a lot of rocks unsuitable for vegetable production or for mechanical weeding). Although the  
392 duration of the study was insufficient to observe the whole crop sequences, this working  
393 scale allowed to observe all crops.

394

395 *Table 2. Agroecological farming practices tested by the four farmers in the pilot group, before*  
396 *and during the study. Practices were classified under general and more detailed categories.*  
397 *For each practice, a concrete example is given.*

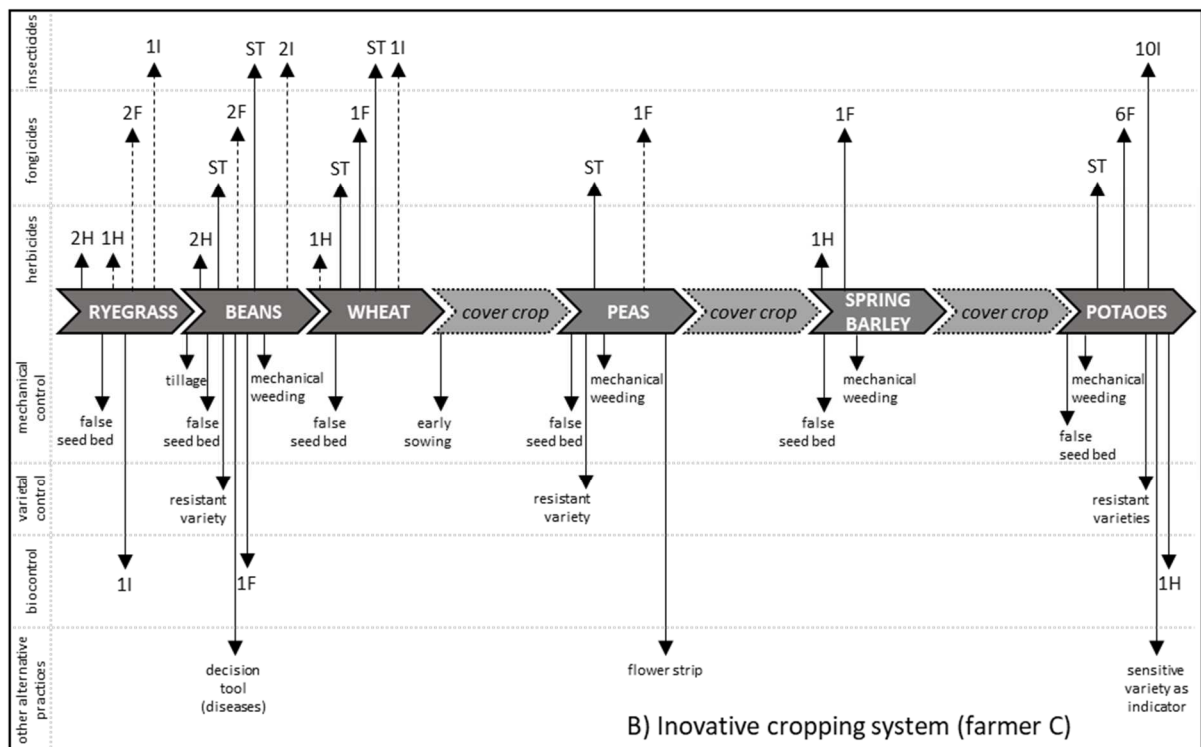
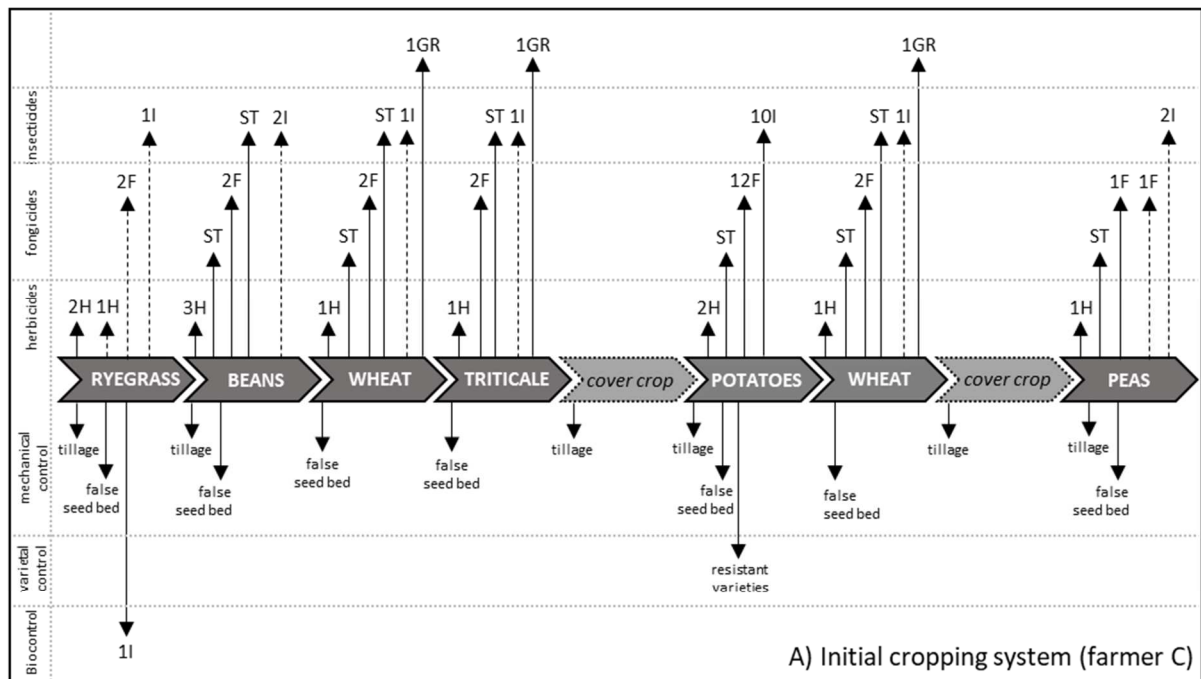
<b>General categories</b>	<b>Detailed categories</b>	<b>Examples</b>
Modification of crop sequence	Shifting the sowing date	<i>Spring wheat instead of winter wheat to reduce the need for fungicides</i>
	Inserting a new crop	<i>Insertion of a buckwheat crop in the sequence to diversify the system with a low inputs crop</i>
	Sowing cover crops	<i>Sowing of an oats-phacelia-radish-sunflower mix during winter to improve soil structure, reduce soil leaching and add nitrogen in the system</i>
Action on the soil	Mechanical weeding	<i>Pea hoeing instead of herbicide use</i>
	Using false seed beds	<i>False seed bed before green bean sowing to reduce the need for herbicides</i>
	Direct seeding into cover crops, precise seeding	<i>Direct seeding of winter wheat into the previous cover crop to keep a ground cover and reduce the need for herbicides</i>
	Reducing conventional tillage	<i>No conventional tillage before cereal crops to preserve soil structure</i>
Choice of varieties and species	Growing a resistant or tolerant variety	<i>Selection of a potato variety resistant to late blight to reduce the need for fungicides</i>
	Mixing varieties in the same field	<i>Mix of wheat varieties to control the development of diseases and reduce the need for fungicides</i>
	Combining species in the same field	<i>Combination of broccoli and Chinese cabbage to control the cabbage root fly and reduce the need for</i>

		<i>insecticides</i>
	Using a susceptible variety as indicator	<i>Sowing of a potato variety sensitive to late blight in a small area to detect the disease and adapt the amount and frequency of fungicides</i>
Adjustment of fertilisation	Estimating nitrate availability during plant growth and after harvest for precise N-fertilisation	<i>Use of an instant measuring device to adjust cauliflower fertilisation</i>
	Using a decision tool for fertilisation	<i>Mapping of nitrogen uptake by wheat crops with drones to adjust fertilisation</i>
	Using a manufactured natural product to promote plants nutrition	<i>Use of the bacterial product Rhizocell® to stimulate green beans root growth and reduce the need for fungicides</i>
Modification of the phytosanitary protocol	Optimising chemical weeding at the crop sequence scale	<i>Intensification of cereal chemical weeding to clean the crop sequence and reduce the overall need for herbicides</i>
	Using a biocontrol product instead of a classic pesticide	<i>Use of the molluscicide Sluxx® on spinach crops</i>
Observation of crops	Pest monitoring and adjustment of treatment thresholds	<i>Monitoring of carrot fly populations with sticky traps to reduce the need for insecticides</i>
	Using a decision-support tool for pest management	<i>Use of the decision tool ScanBean® to optimise Sclerotinia chemical management for green beans</i>
Observation and promotion of biodiversity	Participating in an observation network for farming biodiversity	<i>Sampling of field earthworms with the French national observatory of farming biodiversity</i>
	Installing nesting boxes and perches to encourage the presence of birds	<i>Installation of raptor nesting boxes to enhance voles predation in vegetable crops</i>
	Sowing flower strips	<i>Sowing flower strips along pea crops to enhance the biological control of aphids and reduce the need for insecticides</i>

398

399           Each farmer implemented a set of practices in a consistent way, i.e. following a logical  
400 combination as defined during workshops and represented in decision sketches. In figure 1,  
401 the initial and the innovative (2016 theoretical cropping system) decision sketches of farmer  
402 C are presented as an example. For this farmer, the objectives of the innovative cropping  
403 system were reached thanks to the modification of the crop sequence (order and nature of  
404 cultivated species were changed in order to improve weeds management and reduce the  
405 need for herbicides in the overall system), the suppression or the reduction of chemical  
406 treatments, and the implementation of mechanical weeding, resistant varieties, biocontrol  
407 products and other alternative practices.

408



409

410 Figure 1. Decision sketches designed for farmer C after his workshop. Sketch A is the initial  
 411 cropping system and sketch B is the innovative cropping system (2016 theoretical cropping  
 412 system). In each figure, the crop sequence is written in the middle. The upper part is for  
 413 chemical treatments: growth regulators (GR), insecticides (I), fungicides (F), herbicides (H)  
 414 and seed treatments (ST). Numbers indicate the number of treatments. The lower part is for  
 415 alternative farming practices, categorised in mechanical control, varietal control, biocontrol  
 416 and other practices. Full arrows indicate systemic practices and dotted arrows indicate non-

417 *systematic practices. Fertilisation is not indicated on the sketches because no change was*  
418 *done for farmer C.*

419

420 Fourteen of the 21 agroecological farming practices had previously been put to the  
421 test by farmers in their initial cropping system (Figure 2). Most of them, such as false seed  
422 bed, picking a resistant or tolerant variety or sowing of cover crops, are low-risk, and are part  
423 of the most trialed practices during the study. Due to the high level of technical skills of  
424 several of the farmers, more risky practices were also observed in the initial cropping  
425 systems (e.g. direct seeding into cover crop and mechanical weeding on vegetable crops).

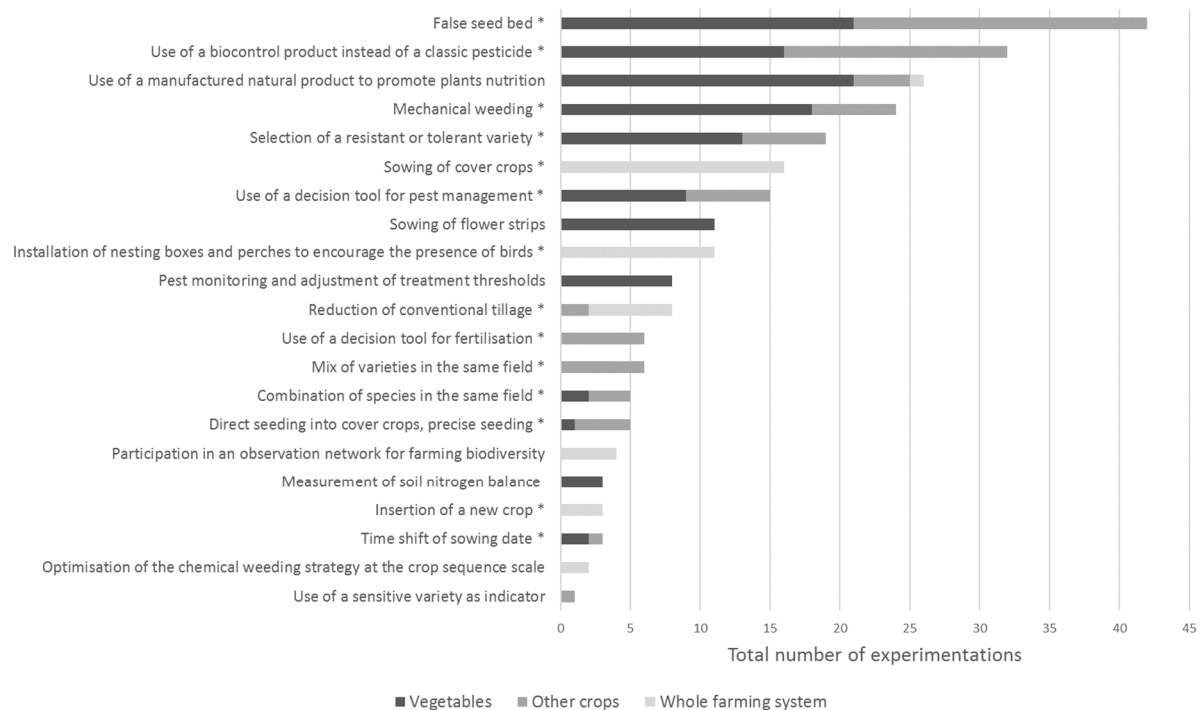
426 Most of the trialed farming practices involved actions on the soil, such as the creation  
427 of false seed beds and mechanical weeding. The cooperative encouraged farmers to use a  
428 natural molluscicide on many crops, which explains the significant use of biocontrol products.  
429 Promoting plant nutrition was also one of the main concerns of the group and especially the  
430 farmers, who used natural products to stimulate root growth, enhance nutrient absorption, or  
431 improve soil structure by promoting bacteria and fungi. Using a decision-support tool for pest  
432 management was also a recurrent farming practice, and a variety of models was proposed to  
433 the farmers. Several practices related to the observation and promotion of biodiversity were  
434 implemented by almost all farmers on different crops. These included sowing flower strips  
435 and installing nesting boxes and perches for birds.

436 Some of the less experimented farming practices required a higher technical level,  
437 such as direct seeding into cover crops, the combination of different species or uptake of a  
438 new crop. Optimising fertilisation was not a priority subject during workshops, so few  
439 practices were targeted to this purpose. Cooperatives decide on sowing dates of industrial  
440 vegetable crops at a regional scale to ensure the timely supply to the factories, so few  
441 changes were proposed regarding crop timing.

442 Fifty percent of the agroecological farming practices were directed to the vegetable  
443 crops, 33% to other crops, and 17% to the whole cropping system. Some practices were  
444 preferentially tested on vegetable crops, such as the use of natural products to promote plant  
445 nutrition, mechanical weeding, selection of resistant or tolerant varieties, the use of decision  
446 tools for pest management, sowing of flower strips, and pest monitoring. In contrast, other  
447 practices were preferentially tested on other crops, such as the use of a decision tool for  
448 fertilisation, mixing varieties, and direct seeding into cover crops.

449





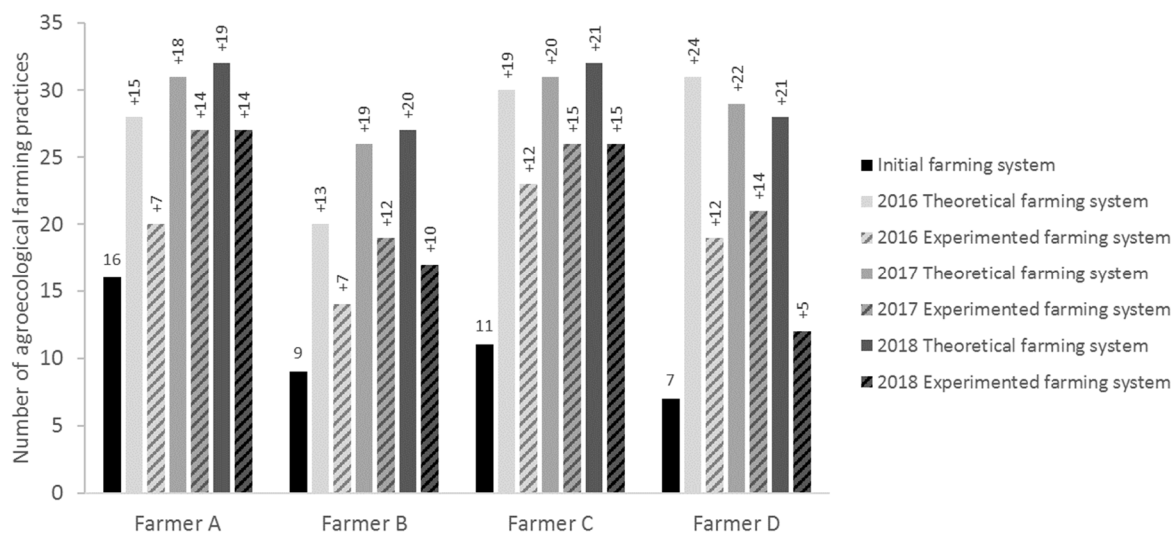
450

451 *Figure 2. Total number of trials for each agroecological farming practice, based on the*  
 452 *detailed categories described in Table 2. One trial is one farming practice used one time by*  
 453 *one farmer on one crop during the study. The application scale is specified with different*  
 454 *colours, separating practices applied on vegetable crops, on other crops (cereals, oilseed*  
 455 *rape, buckwheat, etc.), and at the whole cropping system scale. Practices trialed by at least*  
 456 *one farmer before the study are identified with a star.*

457

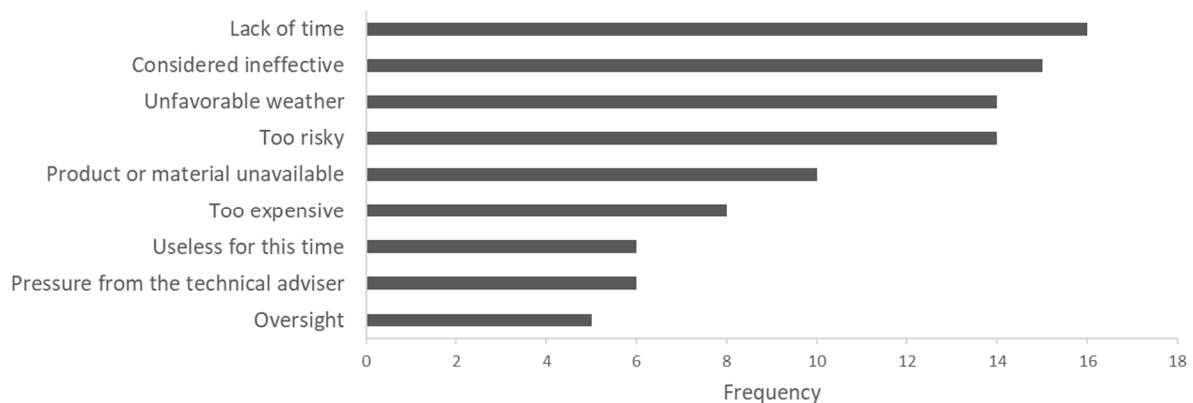
458 Farmers had varying levels of initial involvement in agroecology, as reflected in the  
 459 composition of their initial cropping systems (Figure 3). From 13 to 24 innovative  
 460 agroecological farming practices were proposed during workshops and added to the initial  
 461 ones. During the workshops, more new farming practices were proposed to the farm with the  
 462 most intensive initial cropping system (farmer D) than to the others (24 propositions in 2016).  
 463 The farmers implemented 73% of the farming practices selected for theoretical cropping  
 464 systems during the study (70% in 2016, 79% in 2017 and 69% in 2018). This mean  
 465 percentage varied considerably between farmers, reaching 81% for farmers A and C, 68%  
 466 for farmer B and 59% for farmer D.

467



468  
 469 *Figure 3. Evolution in the number of agroecological farming practices in the four cropping*  
 470 *systems, from the initial approach (before the study) to the last trialed systems (in 2018).*  
 471 *Theoretical cropping systems are those designed during workshops. Experimented cropping*  
 472 *systems are those actually trialed in fields. Numbers indicated are the initial numbers of*  
 473 *agroecological farming practices and the added numbers of innovative agroecological*  
 474 *farming practices. Agroecological practices in the initial cropping systems were not always*  
 475 *included in the innovative cropping systems.*

476  
 477 The main reason for not implementing a proposed agroecological farming practice  
 478 during the study period was lack of time (Figure 4). This included time-consuming practices  
 479 such as mechanical weeding and measuring the soil-nitrogen balance. The farmers also  
 480 found that a significant number of the practices were not effective enough after a first trial,  
 481 and abandoned them the following years. These practices were diverse (mix of varieties,  
 482 pest monitoring, use of decision tools, etc.) and were not the same for all farmers. Weather  
 483 was also a recurrent constraint, especially concerning actions on the soil (e.g. mechanical  
 484 weeding). Both the farmers and their technical advisers were very cautious about any risk to  
 485 production, and this was consequently a major obstacle to some changes in the cropping  
 486 systems. For many of the practices, the farmers and cooperative needed to anticipate the  
 487 steps to implement the change, well in advance, for example to prepare the products (e.g.  
 488 varieties or biocontrol products) and material (e.g. mechanical weeding equipment). This was  
 489 identified as a major weakness of the study since a significant number of agroecological  
 490 farming practices could not be trialed for this reason. Although economic support was offered  
 491 to the farmers for testing new practices, costs remained a big concern, especially concerning  
 492 the use of biocontrol products. Finally some practices were not investigated simply because  
 493 they were useless in a specific context (e.g. when the pest pressure was very low).



495

496 *Figure 4. Reasons given by farmers in 2016, 2017 and 2018 for not trialing agroecological*  
 497 *farming practices proposed in theoretical cropping systems.*

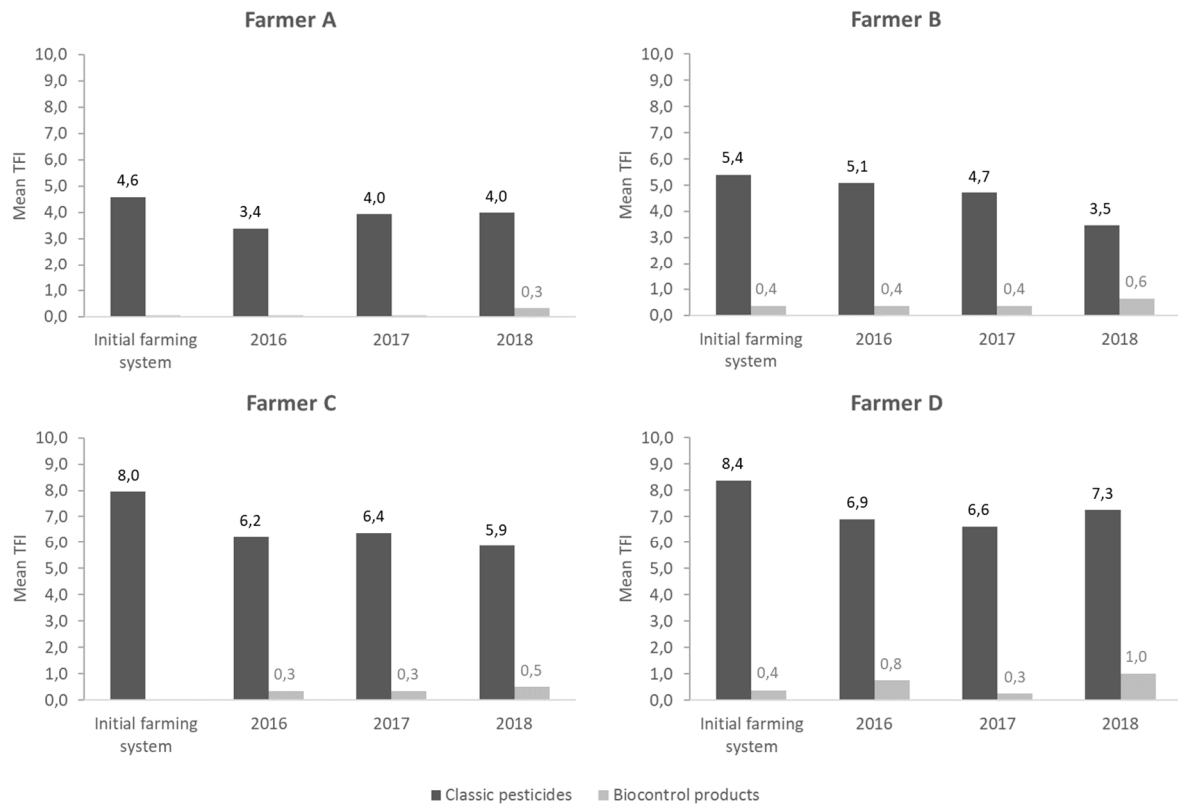
498

#### 499 Cropping system sustainability

500 All farmers reduced their pesticide use during the study (Figure 5), with a mean TFI  
 501 reduction of 15%. However, the farms had varying trajectories. Farmers A and B had the  
 502 lowest TFI regardless of the year, showing their commitment to agroecology. Farmer A  
 503 mostly reduced his pesticide usage in 2016 and then preferred to replace classic pesticides  
 504 with biocontrol products. The TFI for Farmer B progressively decreased during the study.  
 505 This change was partly due to the purchase of a seeder in 2018 to carry out direct seeding  
 506 into cover crops. The high TFI of farm C was mainly due to seed potato crops, which  
 507 required a high level of pesticide inputs. Indeed, late blight and click beetles are two major  
 508 pests of this crop, for which few alternative farming practices are actually available, apart  
 509 from the use of resistant cultivars (for late blight). Nevertheless, farmer C still reduced his TFI  
 510 by 20% and integrated some biocontrol products into his cropping system. Farmer D was the  
 511 least experimental and committed to agroecology at the beginning of the study. His high TFI  
 512 can also be explained by the presence of double crops in his cropping system, i.e.  
 513 successions of two crops in the same field and during the same year (e.g. spinach then  
 514 carrots). The numerous propositions made to farmer D during his workshop allowed him to  
 515 reduce pesticide use, especially at the beginning of the project. His TFI increased in 2018,  
 516 partly because of the use of biocontrol products. This increase was also due to a lower  
 517 support from advisers and researchers during this year.

518 In addition to the trials of agroecological farming practices, it is important to note that  
 519 annual variations in TFI were also related to external and uncontrollable factors such as  
 520 weather and pest pressure.

521



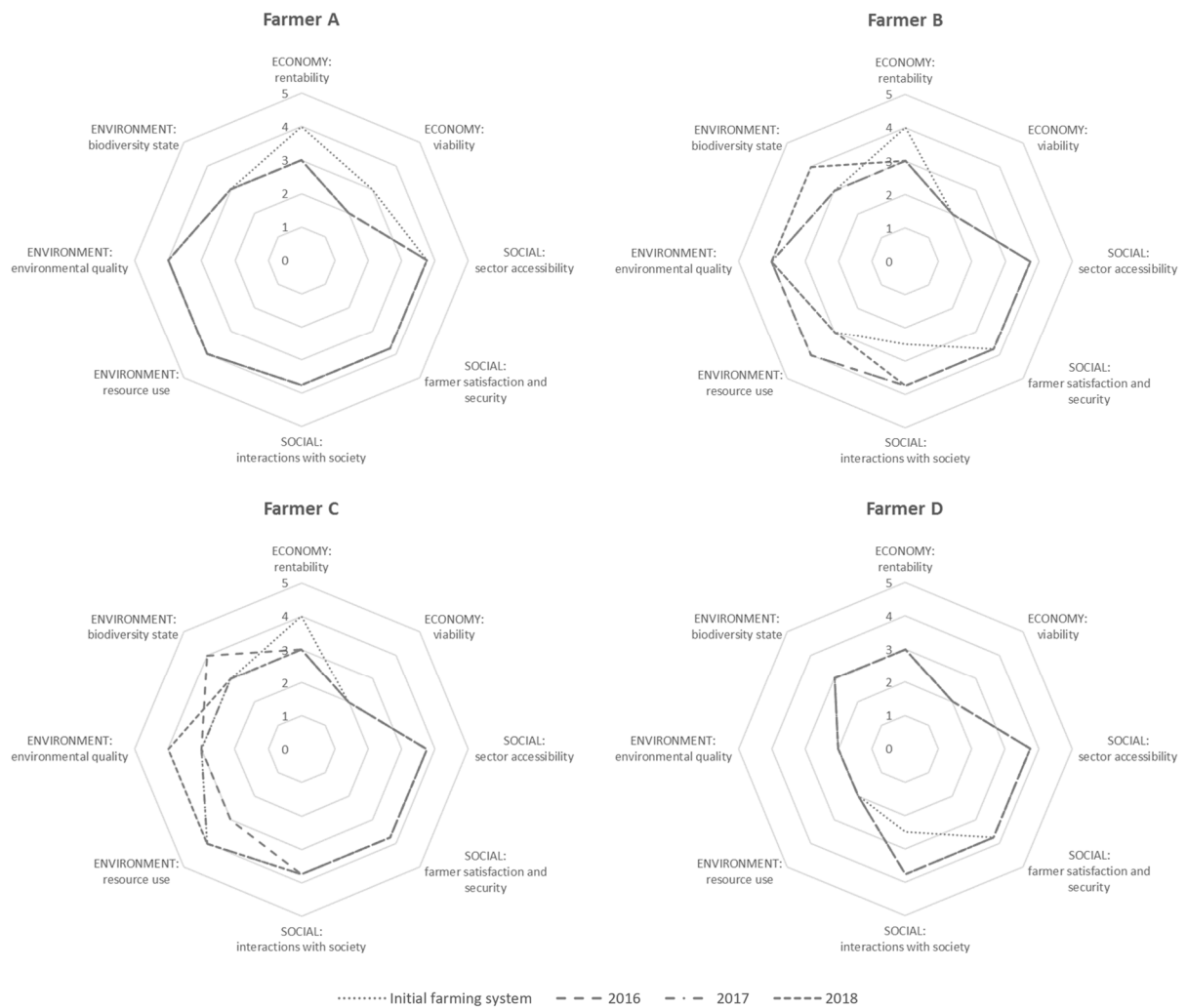
522

523 *Figure 5. Evolution in mean annual TFI (Treatment Frequency Index) for the four farmers*  
 524 *during the study. Initial and trialed cropping systems are shown. The TFI of classic pesticides*  
 525 *(in dark grey) and biocontrol products (in light grey) were calculated separately.*

526

527 Multi-criteria analyses showed that there was no significant change in cropping system  
 528 sustainability (Figure 6), between the initial and the innovative practices, or between the  
 529 three experimental years. Only two farmers enhanced their environmental parameters over  
 530 at least one year. This was related to biodiversity state (farmers B and C), environmental  
 531 quality (farmer C), and resource use (farmer B). Social parameters only evolved for farmers  
 532 B and D, for which interactions with society were higher in all innovative cropping systems.  
 533 On the other hand, the economic profit was lower in all the innovative cropping systems at  
 534 farms A, B and C.

535



536  
 537 *Figure 6. Results of multi-criteria analyses carried out with DEXiPM-FV for the four farmers.*  
 538 *Initial and trialed cropping systems are shown. Rentability reflects gross margin and financial*  
 539 *aid ; Viability reflects economic independence and efficiency ; Sector accessibility reflects the*  
 540 *availability of inputs, workforce, markets and technical advice ; Farmer satisfaction and*  
 541 *security reflects the complexity of cropping systems and associated health risks ; Interactions*  
 542 *with society reflects contribution to employment, acceptability of farming practices by society,*  
 543 *and social value of the surrounding landscape ; Resource use reflects energy consumption*  
 544 *and use of water, soil and mineral fertilisers ; Environmental quality reflects water and soil*  
 545 *quality, and air pollution ; Biodiversity state reflects the abundance and diversity of terrestrial*  
 546 *and aerial species.*

547  
 548 Evaluation of the methodology

549 Based on these results and on discussions with the four farmers, Ardo, Picard and the two  
 550 researchers from INRAE collectively approved the methodology, since it allowed to design  
 551 and test cropping systems that can contribute to initial aims. In spite of the mixed results  
 552 concerning TFI reduction and cropping system sustainability, it was indeed possible to

553 reduce the environmental burdens of farming practices for two of the four farmers involved,  
554 and to anticipate the progressive ban of phytosanitary products thanks to the combination of  
555 various alternative practices. The three collaborators consequently decided to continue the  
556 project by including more farmers.

557

## 558 **DISCUSSION**

559

560 Design of innovative cropping systems for the industrial vegetable sector: what is the  
561 outcome?

562 The 15% mean reduction in TFI obtained from the 21 agroecological practices  
563 included in the innovative systems tested by the four pilot farmers is low compared to the  
564 aims of current government policies. In France, the “Ecophyto plan” aims to reduce the use  
565 of chemical pesticides by 50% by 2025 (French ministry of agriculture agribusiness and  
566 forestry, 2015b). Results recently shown by the DEPHY network showed that a reduction of  
567 38% TFI can be reached for vegetable crops (Eckert et al., 2018). At the same time, some  
568 studies have shown for other sectors that reducing pesticide usage by 42% can be achieved  
569 without negative impacts on productivity and profitability (Lechenet et al., 2017). However, no  
570 studies have been published to date on the specific case of the industrial vegetable sector,  
571 and the TFI reduction was actually interpreted as a satisfactory result by farmers, Ardo and  
572 Picard, given their difficulty in reducing pesticide use. As previously mentioned, the industrial  
573 vegetable sector is characterised by strong constraints related to the expectations of  
574 consumers, the profitability of distributors, the processing steps of industrial companies, and  
575 the agronomic, economic, social and environmental aspects of cropping systems. Such  
576 constraints highlight the limits of the industrial model, as already discussed by many authors  
577 (D'Souza and Ikerd, 1996; Horrigan et al., 2002; Woodhouse, 2010), and could indicate that  
578 a strong TFI reduction in such systems is actually not possible because of lock-in effects  
579 (Fares et al., 2012; Lamine, 2011).

580 Meynard et al. (2017) explain that when a socio-technical system is well-established,  
581 few innovations have a chance of emerging because dominant actors do not want to  
582 question their successful strategies. In this study, dominant actors (Picard and Ardo) were  
583 directly involved in the design of innovative cropping systems and ready to question their  
584 strategies. However, although Ardo and Picard mentioned possible adaptations of their  
585 strategies during workshops (e.g. for Ardo, improvement of optical sorting, and for Picard,  
586 creation of a new agroecological product range), none of these suggestions led to actual  
587 decisions during the three years. This is because the duration and the scope of the study  
588 were too short to make such decisions, which can have strong economic consequences and  
589 would require a long and collective consideration within each company.

590 The multi-criteria analyses carried out as part of the study did not show a significant  
591 improvement in cropping system sustainability, unlike in other co-design studies (Berrueta et  
592 al., 2021; Dogliotti et al., 2014). Although some farmers increased the environmental and  
593 social parameters of their systems, economic performance was identified as a major  
594 weakness. This is due to the cost of alternative biocontrol products (often much more  
595 expensive than conventional pesticides), to the investment needed in specific farming tools,  
596 and to the higher risk of yield losses. In the same way, the practices most often tested during  
597 the study were the least risky ones, *i.e.* those not strongly related to the operation of the  
598 whole cropping system and unlikely to lead to a reduction in production quality or quantity  
599 (*e.g.* false seed bed or choice of resistant/tolerant varieties). This selection shows the natural  
600 reluctance of farmers and technicians to take risks because of potential economic losses  
601 (Chantre and Cardona, 2014). Such observations have already been made in other studies  
602 (Jacquet et al., 2011; Lien et al., 2007; Pardo et al., 2010; Smith et al., 2011), underlying the  
603 difficulty of obtaining satisfactory economic results during transitions to organic or  
604 agroecological farming systems. Fares et al. (2012) demonstrate that the organisational  
605 structure of agrifood systems can indeed be a lock-in for transition and innovation, because  
606 economic investments are hampered by downstream actors.

607 Based on these observations, Ardo, Picard and INRAE finally approved the cropping  
608 system design methodology, arguing that the TFI reduction observed is promising and is the  
609 first step in a potentially larger movement in which other farmers and cooperatives could be  
610 involved. They collectively decided to continue the project for another three years second  
611 phase, with the target to involve more and more farmers. An essential point is that Ardo and  
612 Picard concluded that farmers cannot be asked to change their systems without increasing  
613 the purchase price of their vegetables. Together, they set a percentage increase in the  
614 purchase price of the vegetables produced as part of the study.

615

616 Design of innovative cropping systems for the industrial vegetable sector: what lessons can  
617 be learned?

618 The integration of agroecological practices within the current cropping systems relied  
619 on the co-design methodology proposed by Launais et al. (2014). All collaborators in the  
620 study appreciated this framework and it was considered successful since it allowed the  
621 assimilation of various agroecological farming practices and the reduction in pesticide use, in  
622 spite of the low flexibility of the sector and of mixed economic results. Four methodological  
623 aspects were identified as key points, which should be taken into consideration in farm  
624 system design for industrial sectors: farm system scale, collective work, farm systems  
625 flexibility, and farm systems uniqueness.

626

627 *Farm system scale*

628           The first initiatives for farm system redesign date back to the 1990s (Spiertz et al.,  
629 1996). The systemic approach has been highly encouraged for the last decade because,  
630 compared to an analytical approach, it can facilitate innovation and transition toward more  
631 sustainable systems (Berrueta et al., 2021; Darnhofer et al., 2012; Meynard et al., 2012;  
632 Probst et al., 2012; Wigboldus et al., 2016). During this project, the innovative systems were  
633 designed considering all crops in the sequences, with 55% of new practices targeting  
634 vegetables and 45% the other species. Discussions during workshops and representation in  
635 the form of decision sketches aimed to take into account interactions between crops and  
636 techniques. For instance, when a winter cover crop containing species susceptible to  
637 *Sclerotinia* root rot and damping-off was selected, a biocontrol product was also placed in the  
638 sequence to prevent the development of the disease. As for all approaches based on  
639 collective design of innovating cropping systems, this coherent combination of farming  
640 practices was essential to create robust and credible cropping systems and relied on in-  
641 depth technical knowledge (Meynard et al., 2012; Reau et al., 2012). Moreover, the systemic  
642 approach led farmers and their technical advisers to analyse cropping systems in a different  
643 way, since ‘contract’ crops (vegetables and seed crops) and ‘non-contract’ crops are usually  
644 managed separately (with different technical advisers and for different markets). Working at  
645 the crop sequence scale allowed to make modifications in the management of vegetables,  
646 which is usually locked by specifications. For instance, the composition of crop sequences  
647 can be changed to better manage weeds and reduce herbicide use on vegetables.

648

649 *Collective work*

650           Farmers, researchers, technicians and engineers from a cooperative, an industry and  
651 a distributor conducted this study for three years. This kind of collaboration is rare, and  
652 farmers are more used to a top-down information flow from technical advisers, agribusiness  
653 actors, or politicians (Coquil et al., 2018; Darnhofer et al., 2012; Duru and Therond, 2015).  
654 However, as explained by Lamine (2011), collective dynamics are better at supporting robust  
655 transitions toward agroecological systems. In this study, working collectively allowed  
656 consensual cropping systems to be designed, and solutions to promote agroecology in the  
657 industrial vegetables sector to be thought about collectively. This was possible because the  
658 risk associated with agroecological transition was distributed among stakeholders.

659           With the development of co-design approaches, farmers, technical advisers and  
660 researchers are now commonly involved in the design of innovative cropping systems  
661 (Berrueta et al., 2021; Falconnier et al., 2017; Le Bellec et al., 2012; Lesur-Dumoulin et al.,  
662 2018; Moraine et al., 2016; Reckling et al., 2020). The strong originality of this study is the  
663 participation of a processing company and a distributor. Discussions during workshops



664 showed that Picard was actually not completely aware of agronomic, economic and social  
665 issues inherent to the vegetable production phase, as well as technical limits inherent to the  
666 processing phase. They realised that specifications are sometimes very hard to reach with  
667 these constraints and with a possible transition toward agroecology. For instance, the  
668 complete lack of dead insects in vegetable bags can actually be incompatible with the  
669 promotion of biological control in crops and with the performance of optical sorters used in  
670 processing factories. As explained in the previous section, this awareness did not lead to  
671 actual modifications of specifications requested by Picard. However, they initiated a real  
672 questioning about products from agroecological production, especially with the quality and  
673 marketing departments of the company, which could lead to modifications of their sales  
674 strategy in the years to come. Consumers education campaigns aiming to explain how  
675 farmers produce agroecological vegetables can for instance help in supporting the  
676 development of agroecology (Francis et al., 2003).

677         The presence of Ardo during workshops had a significant impact on the design of  
678 innovative cropping systems. Indeed, the contractual system imposes on farmers precise  
679 specifications defined by industries in order to optimise the processing procedure (Henson  
680 and Humphrey, 2012). Without Ardo, few innovations would have concerned the vegetable  
681 crops themselves, because farmers could not fully exploit all agroecological measures  
682 envisioned during the workshops. For instance, the management of pests is defined in a  
683 precise and collective program that leaves little latitude to farmers, and that has been  
684 modified thanks to the presence of Ardo. In the same way, sowing of vegetables being  
685 organised at the scale of production areas, changing the sowing date of their own crops  
686 could not have been possible without Ardo. This observation raises the problem of the scale  
687 at which design methods are conducted. The management unit for industrials is actually the  
688 batch, and not the crop, the field or the farm (Meynard et al., 2017). In such a context,  
689 collective design should consequently be ideally conducted at the collecting area scale, as it  
690 was already done for other crops (Le Bail and Meynard, 2003; Navarrete et al., 2006).  
691 Discussion about innovative cropping systems also led Ardo to question their process. Their  
692 main challenge concerns the sorting of foreign bodies collected during harvest (plant debris  
693 and animals). This can have strong repercussions on consumers satisfaction, but also on  
694 health. Some weeds, such as *Datura stramonium*, are indeed very toxic and can cause death  
695 if stems, leaves or fruits are left and consumed with the vegetables. However, several  
696 agroecological farming practices (e.g. direct seeding into cover crops, promotion of natural  
697 enemies) may increase the amount of exogeneous materials that cannot be properly sorted  
698 during the process. As for Picard, this questioning did not lead to concrete decisions during  
699 the study, partly because an improvement of optical sorters would require significant

700 investments. However, they could consider it seriously if the continuation of the project  
701 results in the processing of a sufficient tonnage of “agroecological vegetables”.

702         During the study, farmers learned about industrial processes and the need for Picard  
703 to meet customer’s expectations. As explained by Bos et al. (2009), an essential aspect of  
704 design methods is the collective learning, leading everyone to increase their knowledge. In  
705 this study, exchange between collaborators allowed the recognition and consideration of the  
706 constraints of each participant. It helped to create a climate of trust during workshops and to  
707 collectively define the limits of innovation. The four farmers were also very satisfied to have  
708 the opportunity to express their concerns and issues to downstream actors. Discussions  
709 between such different stakeholders are indeed rare, which contributes to the imbalanced  
710 power relationships observed in food industry (Duru and Therond, 2015; Stuart and Worosz,  
711 2012). The four farmers had contrasting experiences and were initially interested in different  
712 farming techniques. During workshops, they naturally shared advice and knowledge, which  
713 highly enriched their innovating cropping systems. Indeed, this kind of “farmer-to-farmer”  
714 learning has already been identified as an efficient way to expand agroecology (Mier y Terán  
715 Giménez Cacho et al., 2018; Rosset and Martínez-Torres, 2012; Sumane et al., 2018).

716         Collaboration between farmers and technical advisers was also decisive because  
717 farmers needed strong support to implement their innovative systems, and especially in  
718 planning and anticipating the needed material, varieties and products. Lack of anticipation  
719 was indeed identified as one of the main weaknesses, leading some practices to not being  
720 tested when advisers were not present enough. Discussions with farmers also revealed that  
721 advice from technicians is widely followed in vegetable crops. The strong influence of  
722 cooperatives on farmer choices is due to the fact that industrial vegetable crops are grown  
723 under contracts, and regularly subjected to important yield losses. Farmers do not want to  
724 risk losing a crop and prefer to delegate the main technical decisions. Indeed, technical  
725 advisers involved in the study were used to make their decisions with a ‘safety first’ strategy,  
726 for instance with a preventive use of pesticides. Based on this observation, we argue that  
727 involving agricultural cooperatives and technical advisers in the design and testing of  
728 innovative contract cropping systems is essential, since farmers decisions are closely related  
729 to advisers decisions. Technical advisers need to be trained in systemic approach and in the  
730 use of alternative farming practices. The importance of cooperatives during the  
731 agroecological transition has already been highlighted by other authors, questioning the top-  
732 down organisation of advisory systems widely used since the agricultural modernisation  
733 period (Brives et al., 2015; Coquil et al., 2018; Del Corso et al., 2015).

734         Researchers finally played a strategic role in the testing of the new cropping systems,  
735 especially the highly innovative practices needing a particular type of monitoring (e.g. the  
736 combination of species to control a pest), or time-consuming practices needing specific

737 knowledge (e.g. participation in a biodiversity observation network). Without their support,  
738 farmers would not have attempted some tricky practices (for instance, the combination of  
739 broccoli and Chinese cabbage to control the cabbage root fly was proposed and supervised  
740 by a researcher and a PhD student). Moreover, involving researchers in farmers' transition to  
741 agroecology is essential, since it can provide a scientific evaluation of the practices (Coquil et  
742 al., 2018). During the study, farmers and their technical advisers indicated that some  
743 agronomical issues constitute technical dead-ends and that they are waiting for innovations,  
744 sometimes in an urgent way because of the upcoming ban on several phytosanitary  
745 products. For instance, banning glyphosate in France will require the development of suitable  
746 machinery to manage weeds in vegetable crops. Organic farmers producing industrial  
747 vegetables are indeed faced with difficult weed management, resulting in lower and more  
748 fluctuating yields than conventional farmers, and higher risk of contamination by toxic  
749 species. Similarly, the promotion of conservation biological control at various scales is a  
750 complex issue that still needs specific recommendations to be used by farmers (Wezel et al.,  
751 2014). Duru and Therond (2015) underlined that knowledge produced by scientists about  
752 biodiversity and ecosystem services is currently too general to be used in the design and the  
753 management of agroecological farm systems. They argue that a great challenge for research  
754 is to develop operational knowledge to help stakeholders in agroecological transition.

755

#### 756 *Farm system flexibility*

757 Two major types of approach regarding the design of innovative cropping systems  
758 have been described in the literature: *de novo* design refers to the design of systems that  
759 break away immediately from existing ones, whereas step-by-step design refers to more  
760 progressive, incremental transitions (Meynard et al., 2012; Meynard and Casabianca, 2011).  
761 In this study, in order to obtain operational and strongly innovative cropping systems in a  
762 short time, the initial desire was to implement a *de novo* design. During workshops,  
763 participants were encouraged to propose strong innovations, breaking with initial systems.  
764 Farmers were then asked to test innovative systems in their entirety from the first year, *i.e.*  
765 implementing all alternative farming practices as soon as possible. However, the three years  
766 of observation showed that only 73% of the agroecological farming practices proposed to  
767 farmers were enforced, with significant variations between years for each farmer. The  
768 reasons for not testing or implementing specific practices were multiple, but mainly related to  
769 available means, organisation and annual context. This result suggests that a *de novo*  
770 design is actually difficult to achieve in this kind of context and short time frame. It is probably  
771 further hindered by the strong regulations associated with industrial production which  
772 hampered transition, and must have contributed to the farmers' path-dependency. This  
773 concept explains that farmers have often difficulties to make their production systems evolve

774 because of the high costs of converting from a dominant model to a new innovative one  
775 (Chantre and Cardona, 2014; Vanloqueren and Baret, 2009). As mentioned before, the  
776 context of this study may also explain the slow progression of farmers. *De novo* approach is  
777 indeed more suitable for model-based design, since it allows a very wide exploration of  
778 technical combinations to be carried out (Meynard et al., 2012). When *de novo* systems are  
779 tested, they are preferentially implemented in experimental platforms where there is no risk  
780 to jeopardise a farmer's production (Havard et al., 2017). In this study, working directly in the  
781 production context seemed finally more suited to a step-by-step approach. It means that in  
782 such systems, a progressive transition is unavoidable. Innovation is more careful but  
783 cropping systems remain more flexible, which facilitates their adoption by farmers (Meynard  
784 et al., 2012). Farmers indeed need time and insurance to adopt new combinations of  
785 practices and check that their system makes sense and is economically secure. In the long  
786 term, it was shown that modifying practices progressively helps create systems that are more  
787 robust and avoid reversible transitions (Lamine, 2011).

788 Farm system flexibility is essential to face annual and inter-annual variations in  
789 weather, pest pressure, and market prices (Darnhofer et al., 2010; Lev and Campbell, 1987).  
790 Due to global warming, ecosystem disruption, and market globalisation, farmers are  
791 increasingly challenged with these types of fluctuations and need to anticipate them. The  
792 contract system and the sensitivity of vegetables to many pests and diseases make farmers  
793 involved in the study particularly concerned with this kind of economic and agronomic risks.  
794 This was highlighted by significant variation in the number of farming practices tested  
795 between years for each farmer. This finding is important since it suggests that agroecological  
796 farm systems cannot be built as unique and static assemblies. Each pest must be managed  
797 considering the varying situations that can be encountered. Although it was not done during  
798 this study, taking time to determine decision-making rules when innovative cropping systems  
799 are designed can strongly help reaching this aim (Launais et al., 2014). Continuously  
800 adapting farming practices to context also requires that crops are observed very regularly  
801 and farmers have access to surveillance networks. In France, farmers can, for example, read  
802 a public bulletin dedicated to pest pressure evolution at a regional scale several times a  
803 week. These tasks are time-consuming and must be taken into account in the evaluation of  
804 agroecological farm system sustainability.

805 During workshops, participants could design innovative and consistent cropping  
806 systems thanks to a large panel of agroecological farming practices. It shows there is  
807 actually some scope to make industrial vegetable cropping systems more sustainable. This  
808 diversity in available practices is important since it increases the possibility for farmers to  
809 select and combine a set of techniques adapted to their aims and to the agronomic and  
810 economic specifications of their farms. During the study, some practices were however

811 abandoned by farmers because they found them either inefficient or too risky (e.g. the  
812 combination of broccoli and Chinese cabbage to control the cabbage root fly). In the same  
813 way, some technical dead ends were identified during workshops, related to material, tools  
814 and knowledge that were not yet available (e.g. the lack of direct seeding equipment for  
815 vegetable crops). Thus, some innovative techniques actually need additional research and  
816 may not be fully operational for periods ranging from a few years to decades. In the long  
817 term, cropping systems need consequently to remain flexible to integrate technical  
818 innovations from research and development. Farmers must be able to easily swap some  
819 practices for others. This relies on a continuous learning process and monitoring of  
820 outcomes. Such skills were indeed identified as a major strategy for strengthening the  
821 adaptive capacity and sustainability of farm systems (Darnhofer et al., 2010).

822

### 823 *Farm system uniqueness*

824 One of the interesting points of this study is the heterogeneity in the farmer pilot  
825 group. The diversity in their profiles was a continuous reminder that each cropping system is  
826 built within a specific context, and for specific objectives. First, the localisation of the farm  
827 implies specific soil and climatic conditions, affecting crops directly (e.g. concerning nutrients  
828 availability) or indirectly (e.g. concerning pest pressure) (Altieri and Nicholls, 2003; Tamburini  
829 et al., 2018). Landscape parameters, such as the abundance and accessibility of semi-  
830 natural elements, can also strongly affect ecological processes related to crops (biological  
831 control, pollination) (Martins et al., 2015; Veres et al., 2013). Otherwise, the innovative  
832 farming practices selected during workshops were often related to the priorities and  
833 preferences of each farmer. Some authors indeed showed that farmers personality,  
834 experience and knowledge can largely determine farm system composition, functioning and  
835 evolution (Edwards-Jones, 2006; Shrapnel and Davie, 2001; Willock et al., 1999). All these  
836 parameters led to contrasted cropping systems, whose heterogeneity is increased in the  
837 industrial vegetable context. Indeed, in the region where the study was conducted, this sector  
838 is characterised by big farms and diversified farm systems, with a minimum of three different  
839 activities such as livestock farming or cereal production (Pierron, 2016). Farmers integrate  
840 industrial vegetable in their systems in order to diversify their crop sequences and to  
841 increase their income.

842 This heterogeneity must be considered during a design process because it is not  
843 possible to directly transpose a farm system from farmer to farmer. A unique and perfect  
844 sustainable agroecological system does not exist, because “*no single package of practices is*  
845 *able to fit the dynamics of every ecosystem*” (Pretty, 2018). On the contrary, there are as  
846 many farms and farmers as good agroecological farm systems to build. This suggests that  
847 innovative cropping system design processes should be organised as much as possible at

848 the farmer scale to take individualities into account (Lacombe et al., 2018). This is especially  
849 true for the industrial vegetable sector because of the high heterogeneity in cropping  
850 systems.

851

## 852 **CONCLUSION**

853 In this study, we showed that designing and testing innovative agroecological  
854 cropping systems for the industrial vegetable sector is possible, and can help finding new  
855 ways to comply with value chain demands, related to the expectations of consumers, the  
856 profitability of distributors and the processing steps of industrial companies. However, some  
857 precautions must be taken to ensure the success of the design process:

858 - Time is needed to build cropping systems adapted to each farmer and compatible with  
859 specifications. There is a time lag from the design of theoretical systems and the period  
860 necessary for farmers to adopt new practices and gradually select the best combination.

861 - Human resources and training are needed to assist farmers, especially during the first  
862 years. They need help planning and anticipating the equipment needed and training to  
863 increase their technical knowledge.

864 - Money is needed, to compensate for the extra time needed to implement new systems, the  
865 rising costs and the higher risk of yield losses.

866 Such recommendations can be hard to follow because time and money are often two missing  
867 parameters when agroecological transitions are initiated, and that is why such processes  
868 must be taken on collectively. In this study, the collaboration of Picard, Ardo, INRAE, the  
869 cooperative and the farmers was essential for making decisions at the sector scale, spread  
870 the risks and create an enduring dynamic. Indeed, in 2019, it was decided to extend the  
871 study to twenty farmers in the sector. Agroecological regulations were developed, which will  
872 have to be followed by farmers who want to join the project and benefit from an economic  
873 revaluation of their vegetables (increase in purchase price). For Picard, this could be the first  
874 step in a broader process, their ambition being to deploy agroecology on a large scale and  
875 meet consumer expectations by offering healthier products. For Ardo, it will be a good  
876 opportunity to make their technical equipment evolve toward the processing of a larger  
877 amount of agroecological products. For INRAE, it presents the possibility to learn more about  
878 transition process in the specific context of industrial farming. To go further, it will be  
879 essential to measure the impact of innovative cropping systems on the marketing aspects of  
880 production, for instance with a monitoring of product quality, production costs and  
881 commercial yields.

882

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890

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# Working group



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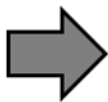
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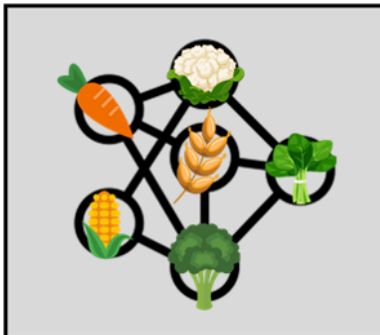
Research team



4 farmers  
Cooperative



1 Co-design of innovative cropping systems



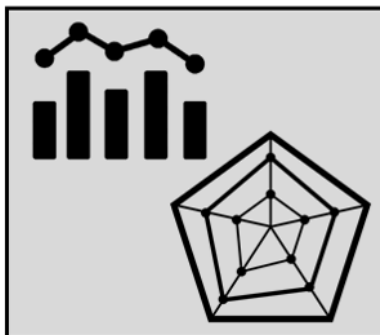
4 collective workshops  
6 vegetable species

2 Experimentation on farm



2 years of experimentation  
21 agroecological practices

3 Multi-criteria analysis



15% TFI reduction  
Economic weaknesses

Validation of the methodology for the industrial vegetable sector → 4 key points:

Farm system  
scale

Collective work

Farm system  
flexibility

Farm system  
uniqueness