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► **To cite this version:**

Maude Quinio, Laurence Guichard, Paola Salazar, Françoise Détienne, Marie-Hélène Jeuffroy. Cognitive resources to promote exploration in agroecological systems design. *Agricultural Systems*, 2022, 196, pp.103334. 10.1016/j.agsy.2021.103334 . hal-03856345

HAL Id: hal-03856345

<https://telecom-paris.hal.science/hal-03856345v1>

Submitted on 29 Nov 2022

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1 Cognitive resources to promote exploration in agroecological 2 systems design

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10 **Keywords:** farming practices, cropping system, biological processes, design-support tool,
11 user-centered design, knowledge structure.

12 **1. Introduction**

13 In-depth changes are required in agricultural systems to face current environmental and
14 socioeconomic challenges. For example, to strongly reduce the use of pesticides in arable
15 systems, it is necessary to change crop sequences and several techniques (e.g. sowing date,
16 cultivar, sowing density, N-fertilizer management), to reduce the risk of pest occurrence and
17 development within the crop (Loyce et al., 2008; Jacquet et al., 2011). Thus, shaping
18 agricultural systems that are less dependent on external synthetic inputs and that rely on
19 ecological processes, such as biological pest regulation (Berthet et al., 2019; Médiène et al.,
20 2011) or environment-friendly nutrient cycling, calls for a huge efforts in innovative design
21 (Meynard et al., 2012). As ecological processes are highly dependent on pedo-climatic
22 conditions, and the choice of alternative techniques varies according to the socio-economic
23 context, such systems need to be tailored to local conditions (L. Prost et al., 2017). Innovative
24 design involves an exploration process to build the disruptive innovations required to satisfy
25 entirely new expectations (Hatchuel & Weil, 2009). In many cases, a successful exploration has
26 been described as including successive periods of divergent and convergent thinking (Cross,
27 1994). In divergence phases, generally occurring at the beginning of the process, the design
28 space (i.e. the space of possibilities) is enlarged through exploration of a wide range of
29 alternatives, whereas in convergence phases, the aim is to deepen, adapt, evaluate and finally
30 define the solutions to the situation at hand.

31 To generate solutions, designers both use and produce knowledge to progressively refine
32 the properties of the object under design (Hatchuel and Weil, 2009). As the features of
33 agricultural systems are highly dependent on the context, exploration should benefit from
34 knowledge that is not only science-based (usually generic), but also experience-based (most
35 often local-dependent) (Doré et al., 2011). Yet the production of scientific knowledge on
36 biological and ecological processes, a key aspect of agroecological systems design, has been
37 neglected for decades due to agriculture's heavy dependency on synthetic inputs, particularly
38 in developed countries. Moreover, the largely local and patchy existing knowledge on the links
39 between such processes and farmers' actions is poorly shared between farmers. Yet as design
40 continues in action (Schön, 1992), observations and feedback from the implementation of
41 innovative, effective and uncommon farming practices can usefully inform design processes,
42 enabling other farmers to learn from pioneering experiences when designing their own systems
43 (Girard and Magda, 2020; Goulet et al., 2008; Salembier et al., 2021; Toffolini et al., 2017).
44 There is great value in sharing situated knowledge and past experiences, most often produced
45 locally (L. Prost et al., 2017). Knowledge-sharing tools and resource-supporting design are
46 increasingly being developed online to widely share science-based or experience-based
47 knowledge. Examples are the online platform Atelier Paysan dedicated to farmer-built
48 equipment for agroecology (Salembier et al., 2020), and the French web tool GECO dedicated
49 to sharing knowledge on agroecology (Soulignac et al., 2017). There is also an increased use
50 of social networks by farmers and advisors, who share past experiences online (Détienne et al.,
51 2012; M. Prost et al., 2017). These experiences are thus widely disseminated. A remaining
52 challenge is however to determine how they support the de-contextualization process described
53 by Toffolini et al. (2017), so that generic knowledge can be derived from them, and applied by
54 more and more farmers. Hence, there is still a need to develop structured design-support tools
55 to help designers in their exploration of knowledge, and specifically to ensure that a diversity
56 of experiences and feedback are capitalized on.

57 To enhance the emergence of solutions within design processes, Hatchuel and Weil
58 (2009) showed the importance of knowledge structures. While designing a new objet, designers
59 establish links between functions, also called functional requirements, and components, named
60 design parameters. For example, in the design of a trailer, one function is to connect it to the
61 towing vehicle, and the dedicated corresponding component is a hitch (Ulrich, 1995). Specific
62 knowledge structures describe such links, referred to as functional diagrams (Ulrich, 1995) or
63 the Suh matrix (Suh, 2001). During the exploration process, the use of new knowledge (e.g.

64 new design parameters) often leads to *knowledge restructuring*: designers add, select and test
65 knowledge, thus reorganizing the links between knowledge and breaking away from
66 determinism existing in previous knowledge structures (Brun et al., 2016; Le Masson et al.,
67 2016). To foster the design of agroecological systems, there is thus a need to develop knowledge
68 structures adapted to agroecology, that are underpinned by these principles, thus favouring
69 exploration processes. Yet proposing such knowledge structures is challenging since the objects
70 to be designed (e.g. cropping systems) are characterized by the importance of their systemic
71 features (Prost et al., 2016). Building consistent interactions between practices, and between
72 practices and the environment, must be at the heart of the design process if efficient
73 agroecological systems are to be achieved. Therefore, knowledge-sharing tools should be
74 designed to support the reasoning behind interactions between disruptive practices, including
75 specific knowledge types and structures.

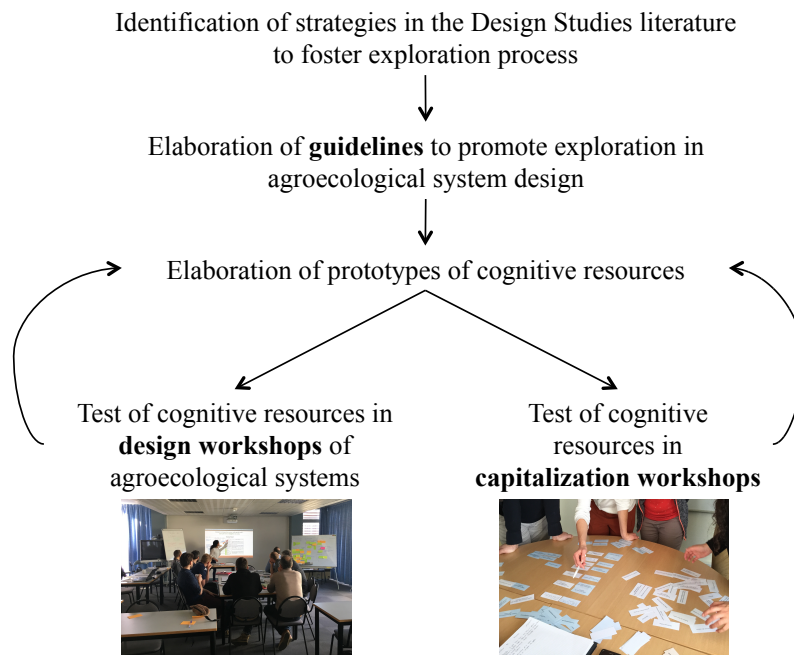
76 As ergonomists have recommended, the development of new tools to support action is
77 improved when their targeted users are involved from the start of the design process (Béguin
78 and Rabardel, 2000). From this user-centered approach standpoint, Cerf et al. (2012) suggested
79 arranging “dialogue” between users and designers through the testing of a prototype of the tool
80 under design and then an analysis of how the tool is used in real or work-like situations. Here
81 we consider tools as knowledge-sharing resources that support the design of innovative
82 agroecological systems, while the users may be farmers, advisors, experimenters, teachers,
83 students, and researchers (all referred to as agronomist-designers). The users may also be actors
84 who own scientific and/or experience-based knowledge and wish to share it, thus becoming
85 contributors to such design-support tools. Therefore, the design of such resources should benefit
86 from the tests around prototypes with the designers of agroecological systems and the
87 contribution of those who capitalize on the knowledge.

88 Our study, based on a user-centered approach, aimed at developing prototypes of cognitive
89 resources to support: i) agronomists-designers of agroecological cropping systems in the
90 exploration of solutions; and ii) contributors in the capitalization on experience-based
91 knowledge to inform exploration. We defined cognitive resources as knowledge-structured
92 resources (i.e. mind maps, diagrams, or tables structuring knowledge). We first drew on
93 theoretical insights from the Design Studies field, on the various ways to foster exploration
94 processes. We then developed three types of generic resources based on these insights, while
95 adapting them to the agroecological field. We also debriefed with targeted users and
96 contributors of the resources (here, farmers and technical advisors) on the uses made of the

97 prototypes in several work-like situations. Finally, we discussed our main findings.

98 **2. Material and methods**

99 Figure 1 describes the sequence of steps, from the identification of strategies from the Design
100 Studies field (Section 2.1), to the elaboration of cognitive resources (Section 2.2) and the
101 testing of the resources in both design and capitalization workshops (Section 2.3).



102

103 Figure 1: Description of the methodological approach

104 *2.1 Theoretical insights on ways to foster exploration*

105 Research from the *Design Studies* field has highlighted three strategies to foster exploration
106 within design processes: the use of expansive knowledge, of functional analysis, and of
107 expansive examples.

108 *The use of expansive knowledge.* Brun et al. (2018) explain how, in architecture, expansive
109 knowledge triggers the generation of original and disruptive ideas during exploration processes
110 and thus supports divergence thinking. In agriculture, while knowledge describing biological
111 processes existing in the field is a strong basis for agroecological systems design, the use of
112 such knowledge outside the designers' initial knowledge base has likewise been shown to
113 enhance the emergence of new ideas (Favrelière et al., 2020; Toffolini et al., 2017) – provided

114 the links between this knowledge and possible technical actions in the field can be highlighted
115 (Quinio et al., 2021). Biological knowledge can thus be seen as expansive, as described by Brun
116 et al. (2018) for other types of expansive knowledge.

117 *The use of functional analysis.* Following this strategy, designers developing a new object
118 perform a functional analysis to establish links between functions and components (Suh, 2001).
119 The correspondence between functions and components can be one-to-one (deterministic
120 links), many-to-one or one-to-many (non-deterministic links), or modular when designers reuse
121 the same component in different design situations – the latest being valued in engineering.
122 Hatchuel et al. (2011) explain that the invention of solutions that differ from existing ones is
123 more efficient when relying on knowledge structures that avoid deterministic and modular
124 links. In agriculture, while designing, agronomists and farmers commonly use process-based
125 functions to interpret the effects of practices implemented by pioneer farmers or experimenters.
126 To sum up, divergent thinking in agriculture should be based on the invention and visualization
127 of new associations between functions and techniques, and adding, where relevant, biological
128 knowledge to these associations.

129 *The use of expansive examples.* While building solutions, designers often use knowledge
130 derived from their own past experiences, and reuse features of prior solutions, referred to in the
131 literature as analogical reasoning (Bonnardel, 2000; Détienne, 2003). By doing so, they transfer
132 some components from a solution that already exists (source solution) to develop and adapt a
133 new solution to the situation at hand (target solution). The source often relates to the same
134 domain as the target (intradomain analogies), but solutions from other domains also help
135 designers to open up the sphere of their research (interdomain analogies), provided they are
136 related, to some extent, to the problem to be solved. Such existing solutions enhance creativity
137 (Salembier et al., 2021), but they may also contribute to fixation effects (Crilly and Cardoso,
138 2017; Ward, 1994), for during exploration processes a frequent obstacle is designers’
139 overreliance on a limited set of known ideas. Jansson and Smith (1991) first showed that, when
140 an example of an existing solution is brought to a design task (i.e. the use of a picture as
141 stimulus), designers have a tendency to copy some features of the example, which are then
142 directly transferred into the novel object under design. The range of solutions generated is thus
143 limited by this initial proposition: designers are influenced by their own “body of knowledge”,
144 and sometimes only apply knowledge from their own field of specialization (Ward, 1994).
145 Agogué et al. (2014, 2011), on the other hand, showed that the emergence of unexpected
146 properties of the object under design could be enhanced by the use of expansive examples,

147 presented as inspiring solutions. For example, in the “egg task”, existing solutions were
148 proposed to participants who were asked to find original ways to ensure that an egg did not
149 break after falling from a high building. The solutions were either restrictive, using classic
150 examples inside designers’ knowledge base (i.e. mattresses on the ground to dampen the shock,
151 parachutes to slow down the fall), or expansive, using innovative examples (e.g. using a living
152 device to transfer the egg). In the study, the designers were given expansive examples that were
153 directly feasible solutions, which enhanced the exploration (Agogu  et al., 2014). To get
154 inspired in design processes, agronomists and farmers sometimes also use examples of rare
155 agroecological systems, already implemented by innovative farmers (Lef vre et al., 2014;
156 Salembier et al., 2020). They generally use such experience-based knowledge to support the
157 adaptation of pre-existing solutions to their new local context (Toffolini et al., 2017); this is
158 referred to as convergent thinking. Pre-existing examples aimed at helping agronomist-
159 designers should therefore be described in such a way that it enhances exploration, while
160 limiting fixation.

161 2.2 Development of cognitive resources

162 Based on: i) the above strategies in the Design Studies literature, ii) types of knowledge
163 used by agronomist-designers – both science-based and experience-based knowledge (Toffolini
164 et al., 2017) –, and iii) previous work describing knowledge structures (Reau et al., 2016;
165 Salembier et al., 2021), we devised guidelines to build three prototypes of cognitive resources
166 (also named knowledge-structured resources). The aim was to support agronomists-designers
167 in their exploration process: the *function-based resource* (FBR), the *biology-based resource*
168 (BBR) and the *experience-based resource* (EBR). We built the FBR and BBR with the intention
169 of specifically supporting divergent thinking, and the EBR to support both divergent and
170 convergent thinking. The three resources differ in their structure and mode of representation.
171 First, the FBR was represented through an exploration tree, as it brings together and shows a
172 range of generic (frequent or rare) alternative techniques contributing towards a design goal
173 that is either broad (e.g. the reduction of pesticide use) or very specific (e.g. the control of thistle
174 in organic cropping systems). Second, the BBR was proposed as a chronological table,
175 describing biological knowledge about pests and natural enemies, organized along their main
176 development stages, as well as their traits and the functions that may influence their
177 development and spread. The BBR finally displays a range of alternative techniques affecting
178 these functions, able to control one pest over time (either a weed, or a disease, or an insect).
179 Such biological knowledge is rarely available to practitioners (mostly published in scientific

180 papers) but has been shown to be useful to design agroecological systems (Favrelière et al.,
181 2020), specifically as pesticide reduction is one of the most widespread issues in agroecological
182 transition. Third, with the aim of sharing know-how from innovative practices, and to foster
183 systemic reasoning, two important features for the development of agroecological cropping
184 systems, the EBR was mapped as a chronological diagram. It was composed of experiential
185 learning generated by the implementation of an agroecological system in a precise agricultural
186 situation. We wanted these resources to be adapted to diverse forms of agriculture that promote
187 natural regulation and therefore less reliance on fuel and chemical-based inputs. We also built
188 these three types of resources with the intention that they would be complementary in their use.

189 *2.3 User tests of cognitive resources*

190 We conducted 12 case studies in France to test the three knowledge-structured resources,
191 between February 2019 and June 2020 (Table 1). The case studies were chosen with various
192 design goals (e.g. broad or specific), designers and contributors participating (e.g. farmers,
193 advisors, experimenters, researcher), objects to be designed (e.g. cropping systems, crop
194 management systems, or one technique), and types of agricultural system (e.g. input-based
195 farming systems, organic or no-till farming systems). We tested the cognitive resources with
196 two types of targeted users: a) designers and facilitators of design workshops who were likely
197 to draw on these resources during their design process, and b) contributors producing one or
198 several resources, who had knowledge and experience, and were either designers themselves or
199 had already supported design processes. Discussions were recorded when authorized.

200 Based on user-centered design (Darses and Reuzeau, 2004), we first organized user tests to
201 introduce users to the resources. Here the users were designers of cropping systems within
202 design workshops (from C1 to C6). The facilitators of the workshops became acquainted with
203 the resources, which were then presented to the designers participating in the collective
204 workshops. We looked at how the resources could fit into their real work situation, for instance
205 what they could or could not do to support the exploration process. For instance, the resources
206 may support divergent thinking by enlarging the search for alternative solutions, or else
207 convergent thinking by selecting and evaluating solution, which are more or less satisfying. We
208 also looked at how users apply the resources for other purposes, to document the designed objet.
209 We then implemented user tests in both individual and collective sessions, with contributors
210 who were participants that had science-based and/or experience-based knowledge (from C5 to
211 C12). We noted the difficulties encountered in capitalizing on knowledge, for example when

212 applying the suggested guidelines to write the content of some resources on specific topics. We
213 also asked contributors how the resources could fit into their real work situation, how they
214 imagined their use, and any difficulties in understanding them. Contributors were technical
215 advisors (C5, C6, C10, C11, C12), the pilot of an experiment in a research institute (C8),
216 teachers (C12) or researchers (C7, C9). Furthermore, the composition of the groups of
217 contributors varied between the cases studied: either advisors only, belonging to the same
218 institute (C11) or not (C5), or a group of more diverse stakeholders (e.g. teachers and
219 researchers in C12). They were either designers themselves or had already facilitated design
220 processes. One or several proposed resources were tested in each case study, depending on the
221 most important lack identified by the facilitator (Table 1): if participants were too set on pre-
222 existing solutions, we tested the FBR; if they lacked biological knowledge in workshops aimed
223 at reducing pesticide use, we tested the BBR; or if they wanted to design a solution for the
224 implementation in a specific situation, we tested the EBR.

225 **3. Results**

226 *3.1 Guidelines to build resources to support exploration in the design process*

227 *3.1.1 Description of the function-based resource*

228 Guidelines to build the three proposed cognitive resources are summarized in Table 2. The
229 *function-based* resource (FBR), also called an *exploration tree*, shows a range of generic
230 technical options for reaching a design goal (Figure 2 for the example on the control of weeds
231 with low herbicide use, in C1). FBR draws from the *mind map* of Reau et al. (2016). The
232 proposed FBR includes reformulations of the design goal in terms of functional descriptions of
233 what has to be achieved (Table 2; G1). For each design goal (tree head), several alternative
234 functions contributing to the goal are identified (tree branches). Alternative techniques
235 contributing to these functions are then proposed (tree leaves), and formulated in a
236 decontextualized form. Functions are worded with a verb expressing an effect on a component
237 of the agrosystem (e.g. disturb the pest and/or deplete soil seedbank), or on ecological processes
238 within the system (e.g. inhibit weed germination).

239

240

241

242 Table 1: Description of case studies with user-designers (from C1 to C6) and contributors (from
 243 C6 to C12) around knowledge-based resources: the function-based resource (FBR), the biology
 244 based-resource (BBR), and/or the experience-based resource (EBR). Due to the covid-19 crisis,
 245 videoconferencing systems have been used in some cases (C4, C9, C12). APAD: association
 246 for sustainable agriculture; CIVAM: centers for initiatives to promote agriculture and rural
 247 areas; GIEE: environmental and economic interest groups; GEPACO: knowledge exchange and
 248 sharing groups, within the French DEPHY Ecophyto network; IFV: French vine and wine
 249 institute; INRAE: national institute for research on agriculture, food and the environment.

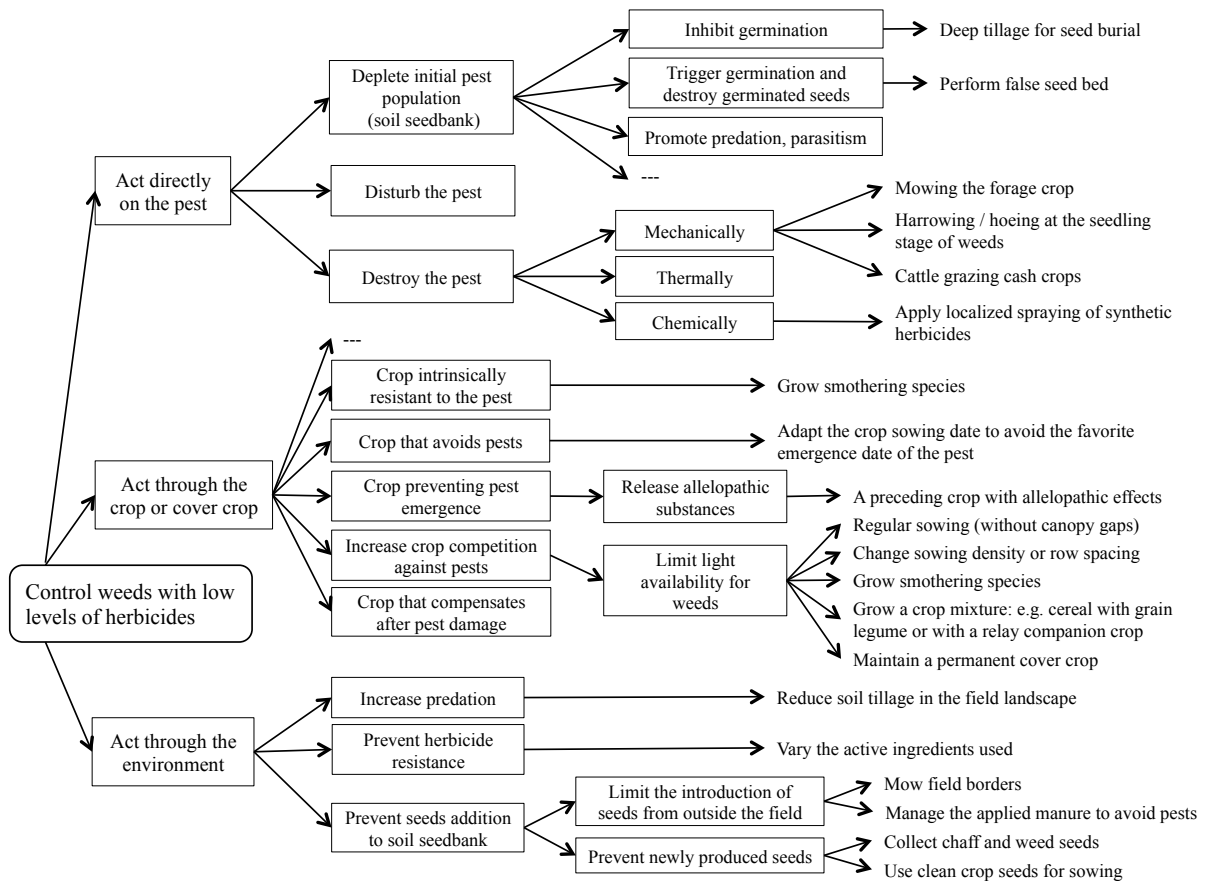
	Design goal to be reached	Institution and location	Type of users	Time scale of data collection	Knowledge-structured resource
C1	Reduce water pollution in a catchment area	Local Chamber of Agriculture – Normandy	Designers: farmers	One day meeting	FBR
C2	Manage a glyphosate-free cropping system (herbicide)	Local Chamber of Agriculture – Normandy	Designers: farmers members of GIEE	One half-day meeting	FBR
C3	Manage a glyphosate-free cropping system (herbicide)	APAD – Hauts-de-France	Designers: multi-actors (farmers, advisors, researchers)	One half-day meeting	FBR
C4	Reduce the use of pesticides	Regional and local Chambers of Agriculture and agriculture secondary school	Designers: multi-actors (advisors, teachers, teacher-researchers, researchers)	One half-day meeting (by videoconference)	EBR
C5	Control wireworms (<i>Agriotes lineatus</i>)	AGT-RT – Hauts-de-France	Designers: advisors	One half-day meeting	FBR, BBR
			Contributor: one advisor	One day meeting	FBR, BBR
C6	Control perennial weeds (<i>Cirsium arvense</i>)	AGT-RT – Hauts-de-France	Contributor: one advisor	One hour meeting	BBR, EBR
C7	Control pollen beetle (<i>Meligethes aeneus</i>)	INRAE – Paris	Contributors: two researchers	2-hour meeting	BBR
C8	Control Carpocapse (<i>Cydia pomonella</i>)	INRAE – Valence	Contributors: pilot of experimental unit	One half-day meeting	BBR

C9	Control gall nematode (<i>Meloidogyne spp.</i>)	INRAE – Avignon	Contributors: Researcher	2-hour meeting (by videoconference)	BBR
C10	Introduce crop mixtures in arable cropping system and vineyards	Members of GEPACO group – whole of France	Contributors: advisors of IVF, CIVAM	One half-day meeting	FBR
C11	Control annual and perennial weeds with a minimum of herbicide use	Regional and local Chambers of Agriculture – Normandy	Contributors: advisors	One half-day meeting	FBR
C12	Reduce the use of pesticides in arable cropping systems	Regional and local Chambers of Agriculture Bourgogne-FC and agriculture secondary school	Contributors: advisors and teachers	Three half-day meetings (by videoconference)	EBR

251 Table 2: Guidelines to build the three knowledge-based resources to promote divergent and/or convergent thinking: the function-based resource
 252 (FBR), the biology based-resource (BBR) and the experience-based resource (EBR)

Guidelines to build cognitive resources	FBR	BBR	EBR	Exploration process	Examples
G1: Provide a functional description of the design goal	X		X	Divergent thinking	To control pests with low amounts of pesticides (here broad design goal), the designed FBR describes the technical options at different time and space scales: act directly on the pest across the whole crop cycle, control the pest through actions on the crop (e.g. cash crop, cover crops, intercropping), or manage the pest through management options at landscape scale or over several years
G2: Synthetizing a range of technical options from different production systems and types of agricultural systems (and the functions that they affect), either stabilized or hypothetical	X	X		Divergent thinking	
G3: Provide links between functions and techniques: one function is associated, when possible, with several techniques (no deterministic links)	X	X		Divergent thinking	Several alternative techniques were suggested to increase crop competition against weeds (function) through the limitation of light availability (function): changing the sowing density or the row spacing, and/or growing smothering species such as hemp, and/or growing a crop mixture, and/or maintaining a permanent cover crop, etc.
G4: Provide non-exhaustive and non – hierarchical inventory of links between function and farming techniques	X	X		Divergent thinking	
G5: Show the links between biological knowledge and farming practices		X	X	Divergent thinking	The average life cycle of 4 weeks of gall nematode (<i>M. Incognita</i>) in summer is a key element to design farming techniques to interrupt its cycle (C9). One function is to attract the larvae in roots of specific attractive plants (e.g. by introducing forage sorghum during summer as an attractive cover crop), and then destroy the trap-plants, including the roots, before the egg production (destroy sorghum within 3 weeks).
G6: Derive and visualize generic knowledge from innovative locally-implemented practices			X	Divergent and convergent thinking	To increase the competition between the cover crop and weeds for light, he planned to sow the Nyger very early (before August 15 th), to ensure a good growth in the early summer. He chose Nyger for its drought resistance (frequent in summer in his situation).
G7: Unravel and visualize systemic interactions			X	Convergent thinking	To leave time to implement several soil tillage operations in summer, while thistle root reserves were at their lowest, the farmer introduced spring pea crop as it is harvested early. Right after the spring pea harvest, he planned to introduce Nyger as a cover crop to cover the soil surface during the post-harvest period.

254 In this FBR, we documented the functions in a homogeneous generic way to encourage new
255 ideas of techniques for carrying out these actions: deplete initial pest population (soil seedbank),
256 disturb the pest, and destroy the pest. These terms can easily be adapted to various pests,
257 whether they be weeds, insects or diseases, thus conferring a generic feature to this FBR, a
258 priori applicable to various designers. To enhance the exploration process, we recommend
259 structuring the knowledge within the FBR according to non-deterministic links: each function
260 is associated with several alternative techniques (Table 2; G3). Some techniques appear several
261 times in the FBR: for instance, the mowing technique is mentioned to destroy the pest either
262 mechanically in the field, or on the field border to limit the introduction of weed seeds from
263 outside the field (Figure 2). In this FBR, there are as few modular links as possible, so that a
264 single technique does not fulfill numerous radically different functions. As this tree was
265 proposed to stimulate exploration, the functions and techniques written in the tree were
266 identified either from scientific knowledge, or from already implemented practices identified
267 by on-farm innovation tracking, or tested on experimental stations (e.g. mixture of a cereal with
268 a grain legume), or else from concepts imagined from the targeted functions, depending on the
269 designer's knowledge (e.g. not fully stabilized knowledge; cattle grazing cash crops; thermal
270 weeding in crop production, Table 2; G2). These trees are not intended to present all possible
271 ways to reach the design goal (we assume nobody can do that). Instead, they provide a wide
272 diversity of functions and techniques aimed at stimulating the design of solutions (either by
273 choosing among those described, or inventing new ones, inspired by the existing ones) by the
274 designer becoming acquainted with them. Last but not least, the FBR represents a non-
275 hierarchical inventory of alternative functions and techniques (Table 2; G4). For the user tests
276 in the various case studies, this resource was developed for various design goals: either broad
277 (e.g. reduce water pollution in C1) or specific (e.g. control thistle in C6), and at various scales:
278 the cropping system scale (e.g. limit nitrogen leaching in C1), and the crop management scale
279 (e.g. introduce crop mixtures in C10).



280

281 Figure 2: An example of the *Function-based resource (FBR)* in C1: *exploration tree* to control
 282 weeds with low herbicide levels (tree head), showing alternative functions (tree branches
 283 framed) and alternative techniques (tree leaves). We built the tree to synthesize the existing
 284 exploration process of the group of farmers in C1. It provides a non-exhaustive and non-
 285 hierarchical inventory of functions and techniques to reach this objective, to which others can
 286 be added (ellipsis).

287 *3.1.2 Description of the biology-based resource*

288 The *biology-based resource (BBR)* is a table dedicated to one specific pest, either a weed,
 289 or a disease, or an insect, and structured by its chronological biological cycle (see Figure 3 on
 290 the example of pollen beetle, in C7). The biological knowledge chosen to be written in the table
 291 concerns life cycle characteristics and functional traits of the pest, that have been shown to be
 292 useful to design strategies to control the pest (e.g. seeds' longevity in soil, to decide plowing
 293 frequencies; capacity of one flower to produce extra floral nectar, to be introduced in flower
 294 strips to attract and feed natural enemies). For each biological stage of the pest (left column),
 295 several alternative functions, contributing to control of the pest at each stage, are identified

296 (mid-column), and alternative techniques affecting these functions are proposed (right column).
297 Functions are formulated through a verb expressing an effect on the pest at each biological stage
298 (e.g. destroy larvae, promote parasitism, repel adults) or on ecological processes of the system
299 (e.g. inhibit pest reproduction). As for the FBR, functions are likewise associated with one or
300 several techniques (Table 2; G3). For example, several alternative techniques could be applied
301 to repel the pollen beetle adults (*Meligethes aeneus*): introduce attractive crops in field borders
302 and/or introduce an early flowering cultivar of rapeseed inside the field and/or introduce a non-
303 sensitive crop, etc. (Figure 3). We built the BBR to shed light on the links between biological
304 knowledge, functions and techniques (Table 2; G5). As observed in the different cases studied,
305 some biological knowledge remains unknown to most designers and is held by only a small
306 number of individuals (depending on designers' knowledge-base). We also wanted this
307 resource to show alternative techniques over time, since several techniques may act on the pest
308 throughout its biological cycle (e.g. not only techniques to limit pollen beetle adults when they
309 are visible and cause damage to rapeseed, but also techniques aimed at limiting the population
310 of pollen beetle larvae, so as to reduce the population of adults the following year). We
311 introduced a calendar in the BBR since chronological reference is useful for farmers, who
312 reason their actions by positioning and organizing them over time. Techniques act at either
313 operational, tactical or strategic levels: their effects are respectively achieved within the crop
314 cycle (e.g. adapt nitrogen fertilization to promote the ability of the crop to compensate for a
315 pest attack), or in the short term (e.g. introduce attractive plants on the field borders to attract
316 adult pests), or in the long term (e.g. lengthen the period between two rapeseed crops to break
317 the cycle of the pests on this crop). As for FBR, techniques were chosen among scientific
318 studies, or among those already implemented by farmers (even pioneering ones) or by
319 experimenters (e.g. introducing attractive plants on the field borders), or were only concepts
320 imagined from the targeted functions (e.g. not fully stabilized knowledge; choose a cultivar
321 with thick flower buds) that might facilitate the emergence and testing of solutions. And,
322 similarly to FBR, BBR proposed a non-exhaustive and non-hierarchical inventory of functions
323 and techniques (Table 2; G4).

Biological stages of pollen beetle (<i>Meligethes aeneus</i>)	Functions	Techniques or combined techniques
J F M A M J J A S O N D	Determine the level of infestation	- Install traps (e.g. yellow bowl)
Emergence and reproductive phase of the adult Adults arrive early April on rapeseed. They move rapidly (1 to 3 km/d) and fly in response to stimuli: visual (yellow color) and olfactory (emission of volatile chemical compounds). Adults puncture flowers buds of rapeseed to feed on pollen, causing their abortions. Females lay their eggs on flower buds.	Repel the adult	- Introduce attractive crops with early flowering date, on the field borders (e.g. turnip rape) - Introduce a small proportion of early flowering crop or cultivar inside the field (e.g. ES Alicia rapeseed) - Introduce non-sensitive or repellent crops such as legumes
	Limit egg-laying	- Choose a cultivar with thick flower buds (under test)
	Promote the ability of the crop to compensate	- Adapt nitrogen fertilization to allow the crop to produce new flower buds and secondary ramifications
	J F M A M J J A S O N D	Destroy the larvae
Larval phase Eggs hatch 4-6 days after laying inside flower buds. The larvae develop and feed on the pollen of rapeseed flowers without causing damage to the crop.	Promote parasitism to limit the population the following year	- Install perennial flower strips to promote the presence of parasitoids (e.g. Tersilochus Heterocerus) ...
	J F M A M J J A S O N D	Expose to predators
Nymph (few weeks) - mid to late May: larvae drop to the ground and pupate - mid June: new adults fly to feed on pollen from other plants and reach overwintering sites.	Disturb the pest life cycle	- Avoid the introduction of a rapeseed crop close to wooded or semi-natural areas (even if these areas are favorable breeding grounds)
	J F M A M J J A S O N D	Promote parasitism
Overwintering of the adults From the end of summer to the beginning of winter, adults overwinter in the soil, or the litter of leaves in wooded or grassy areas. Fungi, such as <i>Beauveria bassiana</i> and <i>Metarhizium anisopliae</i> , infect pollen beetle.		
At the scale of the cropping system	Break the pest cycle	- Increase the period between two rapeseed crops

324

325 Figure 3: An example of the *Biology-based resource* (BBR) in C7, dedicated to controlling
 326 pollen beetle (*Meligethes aeneus*). It is structured according to biological stages of the pest (left
 327 column), shows several alternative functions contributing to control of the pest at each stage
 328 (mid-column), and identifies alternative techniques affecting these functions (right column). It
 329 provides a non-exhaustive inventory of functions and techniques to control pollen beetles.

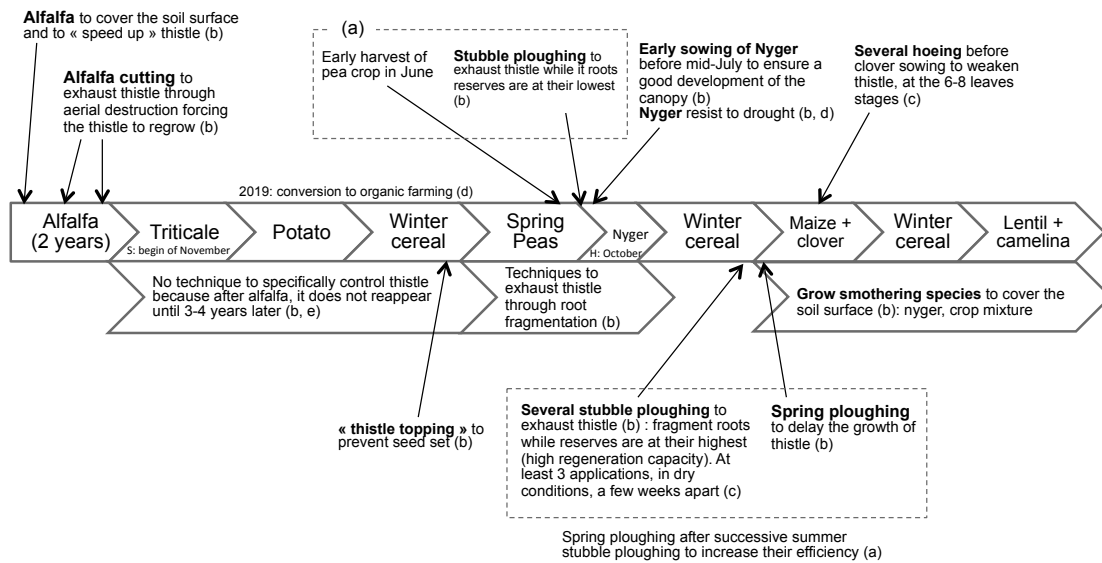
330 3.1.3 Description of the experience-based resource

331 The *experience-based resource* (EBR) shows a systemic combination of different
 332 articulated practices to achieve one or more objectives that are desired and challenging, in a
 333 specific agricultural situation. EBR draws from the *decision scheme* proposed by Reau et al.
 334 (2016) describing a chronological representation of an entire cropping system. The EBR depicts
 335 the farming practices implemented by a pioneer farmer or an experimenter under specific local
 336 constraints (e.g. pedoclimatic and socio-economic context). This resource provides a visual
 337 representation of the chronological elements (successive crops and/or practices applied) of the
 338 described object: part of either a cropping or a crop management system (Figure 4). As
 339 mentioned above, this time-course organization of the practices is highly operational for the

340 farmers, as it corresponds to their calendar of action. The information given in this resource
341 was chosen and formulated on the basis of observations in design workshops, to help designers
342 to decontextualize the site- and time-specific solution experienced, described as the agronomic
343 logic of the pilot (farmer or experimenter), thus facilitating its adaptation to a new agricultural
344 situation. To that extent, it articulates 7 elements (Table 6; G6): (i) the global objective of the
345 design; (ii) the techniques and their combination, that have been specifically chosen and
346 implemented to reach sub-objectives concerning the agrosystem, feeding the global objective;
347 (iii) the reasons why the manager who experienced the described system chose to implement
348 each of the practices, or the combined practices, with a view to reaching particular sub-
349 objectives (e.g. alfalfa is grown to ensure competition against this weed, and is regularly cut,
350 thus depleting thistle root reserves); (iv) the conditions of success and failure of the techniques,
351 which guarantee the achievement of their expected effects, sometimes identified through the
352 implementation and assessment of variants of the technique over years or across fields (e.g.
353 indicators used by the manager to trigger a specific technique, hoeing, when the thistles were
354 at 6-8 leaves stage, the compensation point); (v) the characteristics of the situation that explain
355 some of these options (e.g. the choice of nyger to be sown in summer, as this species is more
356 resistant to drought); (vi) the evaluation criteria the farmer defines from the implementation of
357 each technique, as contributing to the global objective (e.g. the crop or the environment states
358 to be reached: thistle should not appear in his field after alfalfa, as alfalfa is grown to ensure
359 competition against this weed); and (vii) the functional interpretation of the links between the
360 6 previous elements, in order to unravel systemic interactions. We illustrated this EBR resource
361 to synthesize a cropping system designed by an organic farmer to control thistle (specific design
362 goal), consisting of farming practices successfully tested by peers who attended the workshop
363 (Figure 4).

Control thistle in organic agriculture

Farmers' field (northern France), high risk of summer drought (d)



364

365 Figure 4: An example of *Experience-based* resource (EBR) designed in C6: cropping system
 366 designed to be implemented by a farmer in northern France to control thistle in organic
 367 agriculture, based on several successful techniques tried and tested by peer farmers. This
 368 diagram shows: techniques (in bold), combined techniques (framed, a), reasons why the
 369 techniques have been chosen by the farmer (b), conditions of success or failure (c), the
 370 characteristics of the situation that explain some of these particularities (d), and the evaluation
 371 criteria (e). First, the farmer had already introduced alfalfa in his cropping systems to cover the
 372 soil and exhaust thistle (by cutting both alfalfa and thistle, thus forcing it to deplete root reserves
 373 for regrowth). If the thistle had not reappeared two years after planting alfalfa, he advised to do
 374 nothing else in particular. Secondly, the farmer planned to implement solutions to exhaust
 375 thistle at the stage at which the root reserves are at their lowest. Thirdly, the farmer planned to
 376 introduce successively several crop mixtures to ensure good cover of the soil surface.

377 *3.2 Results from tests in design situations: resources support designers and facilitators in*
 378 *their multi-faceted explorations*

379 *3.2.1 Facilitators used the resources to prepare and manage exploration during a*
 380 *design workshop, without showing the whole resource*

381 Facilitators of design workshops (whether advisors or teachers) envisioned the use of one
 382 or several resources to foster the exploration of solutions. After a precise in-depth analysis of

383 each one, some facilitators concluded that they planned to use all three resources to both prepare
384 and manage a design workshop or a training session with farmers (C5, C11, C12). First,
385 advisors proposed to use both the FBR (C11) and the BBR (C5) to prepare a workshop with
386 farmers. They said that these resources would allow them to identify and collect numerous
387 ideas, thus enlarging their own knowledge base. Given their previous experience, they claimed
388 it could be fruitful for them to become acquainted with the various biological characteristics of
389 the life cycle of the pests (BBR) that would be considered during future workshops, as this
390 would enable them to share this knowledge with the participants and thus to further their
391 exploration (C5). Second, facilitators were considering using the FBR as back-up support to
392 propose both functions and techniques that were not spontaneously imagined by participants,
393 thus enlarging the range of alternatives for the designers. For example, a facilitator proposed to
394 deepen a technique mentioned by a farmer to reach the design goal, by identifying one or several
395 function(s) fulfilled by the said technique (C12), and then by asking participants to find other
396 techniques, or combined techniques, that could fulfill the same function (thus moving across
397 the FBR from the right to the left). Another proposition from an advisor was to present only the
398 functional side of the FBR (the left part of the tree) to farmers attending a training session, and
399 ask them which techniques or combined techniques could fulfill the various functions (Quote
400 1, Table 3). This would encourage them to explore various solutions to affect the functions, and
401 not only to propose techniques that they knew impacted the global objective (C5, C11).

402 *3.2.2 Designers and facilitators used the resources to stimulate exploration*

403 Observations showed that facilitators mobilized resources to support divergence, which is
404 particularly difficult when farmers are set on the techniques they already know. Facilitators
405 mentioned that they could present one or several resources during the design process to suggest
406 alternative technical options to the participating designers with FRB and BBR or implemented
407 solutions with EBR (as source solutions), with a view to stimulating exploration (C3, C4, C6).
408 For instance in C3, the FBR (Figure 2) was presented during the design process to designers
409 who were building solutions to eliminate glyphosate use in conservation agriculture cropping
410 systems, considering that pre-sowing tillage and in-crop mechanical weeding are prohibited. In
411 this case, the FBR showed not only existing but also hypothetical solutions related to diverse
412 types of systems (e.g. organic systems, no-till systems). Participants of the design workshop
413 responded by proposing techniques proposed in the tree (e.g. in mixed crop-livestock systems,
414 the cover crop is to be mulched and mown alternatively). Strongly engaged in agricultural
415 conservation, they also expressed their surprise to see in FBR that one of the techniques

416 proposed to deplete soil seedbank was false seed bed, since triggering germination through soil
417 tillage is inconsistent with conservation agriculture principles (Figure 2). They discussed the
418 favorable conditions for seed germination (light and humidity), and argued that other techniques
419 could fulfill the same function (e.g. deplete soil seedbank: seeds in the topsoil are exposed to
420 predation by ground beetles), thus completing the FBR and enlarging their design space. In C1,
421 farmers collectively built cropping systems within one catchment area, and the sharing of
422 solutions from diverse types of agricultural systems (organic or no-till systems) or agricultural
423 production (arable and mixed crop-livestock systems), represented in the FBR shown to the
424 participants, also proved to benefit divergence. Moreover, we found that the identification of
425 generic functions in FBR stimulated designers in their exploration: e.g., the FBR mobilized in
426 C1 aimed at controlling pests, and especially insects, mentioned one generic function, which
427 was to disturb the pest, for example through visual or olfactive disturbance (Figure 2). By
428 definition this function is not suited to weeds, but it gave the designers some ideas: they
429 proposed to diversify sowing dates across years, a technique known to disturb weed emergence
430 (Quote 2, Table 3).

431 Findings showed moreover that the EBR supports both convergence and divergence. In C4,
432 advisors (as facilitators) imagined their use of the EBR to support the reuse of previous
433 solutions, explored in other situations, and to transfer some aspects of the source solution to the
434 situation at hand (analogical reasoning). They believed EBR could orient farmer-designers to
435 select examples that already satisfied farmers who had conditions and constraints resembling
436 those of the situation under design, and get access to evaluation indicators, thus facilitating
437 convergence thinking (Quotes 3 and 4, Table 3). To do so, they assumed that the features of the
438 agricultural situation of the source solution should be described in the EBR, although only those
439 that determined the technical choices made and the results achieved (e.g. choice of Nyger due
440 to high risk of drought in summer). According to them, the description of the conditions of
441 success or failure that had been assessed by the innovative farmer was crucial knowledge
442 (Quotes 5, 6 and 7, Table 3). It allowed for convergent exploration by facilitating adaptation to
443 the situation at hand, and by indicating the precise characteristics of the implementation that
444 would be required in the new situation to reach the targeted result (Table 2). They affirmed that
445 the EBR could motivate participants to test new techniques, as they saw that others, among
446 their peers, had already implemented them with success (Quote 8, Table 3). Last but not least,
447 the description of an implemented solution in the EBR (either a farming practice, combined
448 practices, crop management or cropping system) also fostered divergent thinking by designers

449 who had not previously known about this solution, or the issues surrounding its implementation
450 (Table 2).

451 3.2.3 *Facilitators stimulate interactions over time, within the same group of designers*

452 Facilitators used the FBR and EBR to formalize the outputs of an exploration process;
453 synthesizing and documenting the solutions explored in a design workshop as well as
454 visualizing the designed object (C1, C2, C6, C12). During the workshops C1 and C2, the
455 techniques introduced in each cropping system under design were identified in color by the
456 facilitator in the FBR, thus also displaying the techniques not mobilized in the designed
457 solutions. In C1, in the first workshop without the use of the FBR, farmers designed two
458 cropping systems to limit winter nitrogen leaching, and to be implemented on a farm within a
459 catchment area in Normandy (north-western France). The same group of farmers attended a
460 second workshop, fifteen days later, to pursue the design process using the FBR which was
461 documented by the facilitator. During the first workshop they mainly introduced techniques to
462 enhance crop nitrogen uptake in autumn. For example, they decided to sow a long-term cover
463 crop very early, right after the wheat harvest, to facilitate its growth so that it would quickly
464 cover the soil. Farmers also discussed the introduction of short-term cover crops between wheat
465 harvest and winter barley sowing, which is rarely the case in practice due to a short time period.
466 They also debated the introduction of permanent cover crops, mixed with cash crops, and built
467 either chemical or mechanical solutions to control the permanent cover crop in order to limit its
468 competition with the cash crop (e.g. emergence stage of corn is sensitive to competition). All
469 these technical solutions had been identified in the pre-existing FBR by the facilitators, after
470 the workshop, and the resource was then presented to the same group in a second workshop.
471 This visual display promoted new discussions between the farmer-designers about the
472 techniques avoided during the previous workshop, and led them to pursue the design and raise
473 debates on a subject that had been set aside during the first workshop. Farmers discussed how
474 their fertilization practices throughout the cycle could lead to an excess of mineral nitrogen in
475 the soil at harvest, that would be leachable during winter. They discussed their current use of
476 an available decision-support tool (called Farmstar), and whether it would help them to better
477 manage their nitrogen applications to limit this excess.

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480 3.3 Results from tests with contributors: issues of capitalization

481 3.3.1 Issues regarding completeness and validity of the resources

482 Contributors discussed issues regarding completeness and validity of the knowledge-
483 structured resources as both limits and encouragements for others to contribute. The
484 information given in FBR and BBR is not exhaustive: some functions were not associated with
485 any technique. For instance, to date, no solution was known by the contributor in C7 to promote
486 parasitism of pollen beetles during winter by fungus (Figure 3). The interviewed contributors
487 believed that this could encourage other contributors to fill the blanks, if they had the
488 knowledge. Moreover, in all cases, they expressed concern about the description, in the FBR
489 and BBR, of techniques and functions under investigation, because their effects to reach the
490 targeted goal were unknown, which meant that this was not fully stabilized knowledge (Section
491 2.1). Some contributors assumed that the resources should help farmers to easily discern
492 between highly effective and less effective techniques (and, to some extent, unknown effects),
493 and discussed using a color code to distinguish between them (Quotes 9 and 10, Table 3). For
494 instance, in C5, to control wireworms (*Agriotes lineatus*), the contributors identified techniques
495 that are being studied as biocontrol methods, such as the introduction of predators into the soil,
496 or the nematicide effect of biofumigation, but the group had no information about their
497 effectiveness (e.g. nematicide effect of castor oil cake). Others mentioned that the efficiency of
498 the technique would depend on the farmer's target, which could vary considerably (for example,
499 as some farmers wished to see no weeds in their fields, while others accepted the presence of
500 weeds, they would not all assess the proposed techniques on the same basis, Quotes 11 and 12,
501 Table 3).

502 Moreover, the collective elaboration of the resources helped to clarify and complete its
503 content (e.g. formulation of the design goal Quote 13, Table 3). Contributors collectively
504 reviewed resources that had been built by previous contributors (C5 and C11 in face-to-face
505 meetings, C12 in videoconference), thus enriching them. For example, in C5, advisors revised
506 the BBR aimed at managing wireworms in legume production. One of them shared his
507 experience-based knowledge about the biological cycle, and thus completed the BBR with
508 supplementary techniques to control this pest (e.g. sow barley between rows of maize to protect
509 root development of maize). This biological knowledge was shared only with participants of
510 the working session, yet was identified by them as essential in designing new control strategies.
511 They therefore agreed on the importance of sharing it widely within this type of resource. In

512 C12, while reviewing the EBR, we found that discussion between participants improved both
513 the understanding of the source solution described to control weeds without glyphosate, and its
514 formulation in order to facilitate reuse of the EBR by other designers. The expected results were
515 clarified (e.g. satisfaction indicators of the pilot farm that had experimented with the described
516 solution: no emergence of ambrosia or of perennial weeds), as were the conditions that triggered
517 use of the techniques (e.g. apply a roller at the flowering date of the cover crop, which is a more
518 sensitive stage). In C11, during a collective session between advisors to build a FBR dedicated
519 to controlling annual and perennial weeds with a minimum of herbicide use, the participants
520 had to combine cards describing either pre-defined functions or else techniques. During the
521 session debrief, participating advisors believed that the use of cards accelerated the building of
522 the FBR, and refrained from suggesting further functions and techniques, that were not included
523 in cards (Quote 14, Table 3). These interactions allowed debates and learning processes
524 between them. We also found that the review of the EBR was enriched in C12 with comments
525 from participants who had not attended the design workshop, and needed supplementary
526 information to understand.

527 3.3.2 *Issues about the value-laden nature of the resources*

528 As explained in Section 2.1, we deliberately chose to enhance divergent exploration by
529 depicting, in the FBR and BBR, alternative solutions relating to different types of agricultural
530 systems or production systems. We found that several contributors were reluctant to integrate
531 solutions from diverse and possibly incompatible agricultural systems. For instance, in the BBR
532 used in C5, advisors depicted only techniques relating to vegetable production, as they
533 considered that farmers would not be interested in solutions relating to other production
534 systems, such as arable ones. Similarly, in C3, while building the FBR to prepare a workshop
535 with farmers in no-till systems, the facilitator decided to maintain but to shade solutions that
536 did not belong to conservation agriculture. He/she considered that they did not match the
537 guidelines of the association for sustainable agriculture (no soil scratching allowed) or farmers'
538 commitment toward no-till. The facilitator in C1, on the other hand, built a FBR to synthesize
539 farmers' exploration during a workshop, and to encompass all solutions relating to diverse types
540 of agricultural systems (biological input- and biodiversity-based farming systems) and
541 production systems, all in the catchment area. Similarly, in C10, in a FBR, the advisors brought
542 in alternative solutions from various agricultural systems, such as arable cropping systems and
543 vineyards. This group thus brought together voluntary actors around the introduction of crop
544 mixtures, all belonging to a French DEPHY Ecophyto network, which led them to build the

545 resource in a generic way (i.e. they chose generic functions peculiar to all or only one
546 agricultural system).

547 3.3.3 *Issues about the visualization of agronomic/systemic interactions*

548 Last but not least, contributors pointed out that both the FBR and the BBR neither
549 considered nor represented interactions between functions to reach the design goal (Table 2;
550 Quote 15, Table 3), or between practices to reach one function, or between practices and the
551 environment. They agreed on the value of the EBR as a complementary resource to highlight
552 these interactions. They all mentioned that the identification of such consistent interactions,
553 needed to reach the targeted goal, is not an easy task (C4, C12). For instance, a contributor in
554 C12 noted that, to control grass weed, the wheat sowing date was postponed till the beginning
555 of November. Participants decontextualized this situated knowledge and highlighted an
556 essential interaction between two practices to control grass weed: the farmer introduced stubble
557 plowing several times during the intercrop period (false seed bed), right before the sowing of
558 wheat, which was thus delayed. In C4, advisors and teachers mentioned that the ideas put
559 forward in the exploratory part of a design process, during a workshop, never concerned a whole
560 cropping system (even if the object to be designed was a whole cropping system). Since there
561 was no attempt to duplicate an entire cropping system already implemented elsewhere, they
562 argued about the appropriate scale of the object that was relevant to be detailed in the EBR.
563 They proposed that either a single farming practice, a consistent combination of practices, a
564 crop management system, or a small part of a cropping system (sub-systems, e.g. a crop with
565 its preceding and following crops) should be relevant and more useful to be described in the
566 EBR (Quotes 16 and 17, Table 3). To summarize, we found that these resources fostered a
567 learning process, such as learning about systemic reasoning, and encouraged contributors to
568 evaluate their solutions and justify their choices (Quotes 18, 19 and 20, Table 3).

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574 Table 3: Selection of interactions during the user tests

Description	Quotes
Quote 1 Section 2.2.1: Present the functional side of the FBR (left part of the tree)	I'd show the exploration tree without the techniques, only the objective and the functions, and ask farmers "what techniques are you using today, or planning to use?" (C11)
Quote 2 Section 2.2.2: Generic functions foster divergent thinking and enlarge the search space	"I think it's a pity that we didn't carry on the discussion about the "disturb the pest" function, because I believe it's an interesting option that's rarely discussed, to diversify the species and the sowing dates inside the crop rotation, to insert "two winter crops – two spring crops" in succession, all of which disturb the pests." (C1)
Quotes 3 and 4 Section 2.2.2: EBR fosters convergent thinking	"I think it is important to get a better understanding, because if you have a stony soil, or if you're located in a breeding area, it gives additional detail on the constraints or on the success factors of what happened." (C12) "During design, while searching for experience-based resources, I won't necessarily use a geographical search criterion. I'll use a soil agronomic potential search criterion, or a criterion around agronomic constraints, like a soil that can be drained, a stony soil. The climate can also be an influencing factor." (C12)
Quotes 5, 6 and 7 Section 2.2.2: Formulation of the conditions of success or failure	"The success or failure factors could be contextual elements, or elements related to the implementation, there can be so many different things that make an experience a success and this really needs to be highlighted when sharing knowledge." (C12) "What does the field look like? What was noticeable in the observations made? What the field looks like is very impactful. This is what we would need. The different key states of the field, key moments when the field should look like this or like that..." (C12) "It can be interesting, the notion of annual rate of decline of weeds, which matters to farmers engaged in agricultural conservation. In no-till farming surface seeds are in the topsoil, so weed management will be easier with the increase of the annual rate of decline." (C3, preparation session)
Quotes 8 Section 2.2.2: The reuse of experiences	"I facilitate local communities of farmers. Because we share experiences that are closer to them, it's easier for them to think about how they can be reused. We often hear "it's not the same where I am" " (C12)
Quotes 9 and 10 Section 2.3: Use of color codes to determine the effectiveness of techniques to achieve a function or objective	"A color code could facilitate its use, indicating if the technique is rapidly accessible in my fields, because I own some mechanical tools, and other techniques, for instance thermal destruction is on the contrary inconvenient, and expensive." (C2) "If I understood correctly, you wrote that early sowing is an effective means to control wireworms, but in organic agriculture the sowing is delayed, to control weeds, warmer soil for faster growth, so you can also adapt the sowing depending on the field. " (C5)
Quotes 11 and 12 Section 2.3: Formulation of the expected outcomes	"Knowing when the farmer is satisfied with the weed management, there are key moments to assess that, which can be very specific to each farmer or shared within the community of agronomists." (C12) "I believe it is important when sharing experiences to be specific about the expected outcome, it helps understand the agronomic logic of the people conducting and steering the cropping system, so that what this experience is about is extremely clear and we can then either adapt it or transfer it elsewhere. The same goes for discussions with farmers about weed management, depending on what they want to achieve in their field, between the farmers wanting no weeds at all, or tolerating some, the logic that each

	farmer will apply is different.” (C12)
Quote 13 Section 2.3: Formulation of the design goal	“Sometimes, farmers have difficulties expressing their own goals, and showing them how others may have written their goals may enable them to project themselves in terms of their expectations.” (C12)
Quote 14 Section 2.3: Use of cards to collectively build the FBR	“Because I had ready-made cards, I didn’t really have the opportunity to think by myself, to think it through. I believe that it could be interesting to leave time to search for solutions to the design goal, and only after a while show some ready-made cards to bring in other ideas.” (C11)
Quote 15 Section 2.3: Interactions between functions to reach a design goal are not illustrated in FBR	“It’s interesting, but we only consider the pest, and then the crop, without discussing the interaction between the two. To control flea beetle, I can’t choose the function 4, and the function 3 can be insufficient in case of bad weather conditions.” (C1)
Quote 16 and 17 Section 2.3: Appropriate scale of the agronomic object described in EBR	“When designing a cropping system, we don’t seek to directly copy/duplicate a cropping system already implemented elsewhere” (C12) “I use elements, components of a system and I like to understand why one component leads to a given outcome, which processes are documented, so that it can be used at a later stage and we know exactly why.” (C12)
Quotes 18, 19 and 20 Section 2.3: Resources promote debates and learning processes	“What I liked in the exercise, was the discussion between all of us. It’s the exercise of designing the exploration tree that’s interesting.” (C11) “The results must be clear and precise, as it is important to have an idea of the expected outcome, as well as of the outcomes actually achieved when implementing innovative techniques” (C12) “To take a cooking analogy, there are specific indicators that my choux pastry is ready, there are indicators on the recipe process and in the end there is the indicator ‘my pastries were very good’, and these are different types of indicators. This is the distinction between process management indicators and outcome indicators.” (C12)

575

576 **4. Discussion**

577 We suggest guidelines to build cognitive resources. However, as our results showed the
578 importance of the social dimension both in the use and the elaboration of the resources, we have
579 organized this discussion into two sections: the cognitive and the social dimensions of the
580 resources. We, for the first time, investigated the development of guidelines to build the three
581 knowledge-structured resources to support exploration in the design process toward
582 agroecology (Section 3.1). We highlight issues about the collective elaboration of such
583 resources, made by several communities of users, either contributors, as designers of
584 agroecological systems, or facilitators of design workshop (Section 3.2).

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586

587 *4.1 Cognitive dimension of the resources: learning and shades*

588 We built three cognitive resources with specific knowledge structures, to enhance
589 exploration in many ways. In the following, we reconsider the guidelines to build resources
590 (Sections 4.1.1 and 4.1.2). We then discuss the complementarity between the resources (Section
591 4.1.3)

592 *4.1.1 Guidelines regarding the use of functions in the design process*

593 We recommended to build resources using functions targeted by disruptive practices (G1
594 and G3, Table 2). This has been studied extensively in the literature, in both the agronomic and
595 the design fields (Gero and Kannengiesser, 2004). For instance, the Suh Matrix has been
596 promoting in engineering design and is grounded on the use of functions to model an object
597 (Suh, 2001), the functions of the object are associated to its components. In our study dedicated
598 to agronomy, components refer to farming techniques or components of the agro-ecosystem
599 (e.g. biological organisms), and functions refer to an effect on a component or an effect on
600 biological, ecological and physico-chemical processes characterizing the agro-ecosystem. The
601 same link between functions and components was already highlighted in the trait-based
602 approach, developed in ecology, and then adapted to agronomy (Damour et al., 2014;
603 Tribouillois et al., 2015): traits were either morphological, physiological or phenological
604 characteristics of individual organisms (Garnier and Navas, 2012), and were used to identify
605 the best species to provide some services in the agroecosystem. However, the function-based
606 reasoning has been shown to be insufficient to support innovative design; designers are
607 encouraged to create both new functions and new components, and thus depart from the existing
608 determinisms (Brun et al., 2018), supporting divergent thinking. Agronomist-designers (i.e.
609 farmers or advisors) determine: i) the functions that could be supported in the new cropping
610 systems under design, as they play a key role in spelling out the desired objectives; and ii) the
611 technique or the combination of techniques contributing to these functions (Dumont et al., 2020;
612 Toffolini et al., 2017). Our findings also show that the function-based reasoning, which relies
613 on the exploration of new associations between functions and techniques, and adding, where
614 relevant, biological knowledge to these associations (G5, Table 2), successfully enlarged the
615 design space. Facilitators encouraged designers to propose unknown technical solutions (or
616 combined farming techniques) targeting a given function, and thus to create new associations
617 between functions and techniques. This is linked to the fact that, in agroecological systems, one
618 function can often be achieved by various techniques (e.g. Verret et al., 2020) and, conversely,

619 one technique often affects several functions (e.g. the multiple functions of legume living mulch
620 intercropped with oilseed rape (Lorin et al., 2016)). Another reason may be the specific
621 characteristics of the objects of agroecology, as the effect of one or combined practices to reach
622 one function are dependent on the context of application, especially due to the interaction
623 between the uncertain and unpredictable environmental conditions and modalities of
624 implementation.

625 Moreover, another guideline (G4) proposes the provision of a non-exhaustive and non-
626 hierarchical inventory of links between function and farming techniques, that highlights
627 knowledge gaps. The aim is to help agronomist-designers to think out-of-the-box without
628 providing “ready-made solutions”. Our user tests showed that the identification of knowledge
629 gaps in the resources is not enough to encourage exploration of new functions or components.
630 It is additionally necessary to support collective knowledge sharing (Ingram, 2008), and its
631 facilitation, to inject new knowledge into the design process.

632 *4.1.2 Guidelines regarding the description of implemented solutions*

633 Agronomist-designers often rely on examples of solutions, such as an entire cropping
634 system or sub-systems already implemented by a farmer in a particular situation to reach a
635 desired objective. One example describes site- and time-specific solutions already implemented
636 by a farmer, which usually cannot be directly implemented elsewhere as it is mainly composed
637 of situated knowledge. Numerous and diverse resources have been developed by R&D to
638 document site- and time-specific experiences, such as those identified by Salembier et al. (2020,
639 2021), but we do not know of any feedback about their reuse by others in design processes.
640 User tests have shown that example solutions fostered divergent thinking by suggesting
641 solutions outside designers’ knowledge-base, with unexpected properties and with candidate
642 functions or components to the system under design. On the other hand, example solutions
643 described in EBR resources could partly help convergence thinking, that is, to select, adapt, and
644 evaluate solutions to the situation at hand (Cross, 1994). Our research provided guidelines to
645 build an argued description of the implemented techniques (and not only the list of these
646 techniques, G6, Table 2), to facilitate its adaptation and transfer elsewhere (referred to as
647 analogical reasoning). The capitalization on experience-based knowledge (e.g. the conditions
648 of success and failure of the techniques, which guarantee the achievement of their expected
649 effect), help the designer to tailor the source solution to his/her own situation, thus feeding
650 design by action (Schön, 1992). It also seems important to highlight the fact that convergent

651 thinking can be supported by other tools (e.g. modeling for an ex-ante evaluation in Colnenne-
652 David and Doré (2015) and Pelzer et al. (2017)).

653 4.1.3 *Complementary features of cognitive resources*

654 We did not investigate the use of combined resources in design workshops to assess the
655 complementarity between cognitive resources. Designers often use several resources to support
656 the design process - e.g. Mymyx approach based on several resources (Chave et al., 2019). The
657 three cognitive resources displayed diverse types of knowledge (e.g. biological knowledge,
658 functions characterizing the agroecological system or some of its components, and action-based
659 knowledge) and knowledge structures (e.g. design goal-functions-techniques links, biological
660 knowledge-functions-techniques links, and function-effect of the function after implementation
661 of a cropping system). In our study, each resource is related to one mode of representation:
662 exploration tree for FBR, chronological table for BBR, chronological scheme for EBR. We
663 believe that this diversity, in terms of the nature, structure, and representation of knowledge, all
664 present in the three resources, fosters the exploration process by encouraging designers to
665 invent new associations between knowledge, and to depart from existing determinisms. We
666 mostly investigated the use of each resource individually in several design situations, but our
667 results indicate that the resources have complementary features, and that designers could benefit
668 from shifting back and forth between the three types of resources, which would be facilitated
669 when implemented in a single tool. Further research could be conducted to investigate the use
670 of combined resources in design situation.

671 As some knowledge used to build the resources come from farmers' experiences or
672 observations, it may be derived from on-farm innovation tracking methods, seeking to identify
673 innovative practices of pioneer farmers and to produce generic knowledge (Salembier et al.,
674 2016). This method has been shown to derive various types of agronomic outcomes (e.g.
675 testimonies, agronomic logics underlying actions, ranges of technical options able to reach one
676 target) which are considered useful to feed the design process (Salembier et al., 2021; Verret et
677 al., 2020). Yet, the diversity of resources is not easy to use by farmers or advisors: more
678 standardized resources could support them in finding knowledge in a large on-line platform.
679 Moreover, it is not easy to identify, from the analysis of an innovative practice, which
680 information should be given to future users to support them in the design of their system. Thus
681 the complementary knowledge-structured resources proposed in our paper could be considered
682 as standardized frames supporting "trackers" in the formalization of their outcomes: for

683 instance, the EBR could capitalize on on-farm innovations, or the FBR could synthesize the
684 cross analysis of several innovations, as proposed in Verret et al. (2020). The homogeneous
685 form of the proposed resources should facilitate the work not only of designers, as they propose
686 new knowledge in similar forms that are easier to depict/understand in a tool, but also of
687 contributors, as they constitute guidelines to formalize complex knowledge.

688 *4.2 Taking into account the social dimension of resources*

689 *4.2.1 Resources as part of socio-technical system*

690 Our findings suggest that the knowledge-structured resources support exploration within a
691 group of designers, and revive further exploration over time (use of FBR in C1). We assume
692 that the reuse of FBR by the same facilitator in other design situations (with other designers),
693 or by another facilitator in his/her own design situation, could support and facilitate exploration.
694 However, the user tests captured some issues in the direct use of the resources in collective
695 design situations: designers discussed not only the value-laden nature of the content but also
696 the completeness and validity of the knowledge depicted in the resources. Values are
697 conceptions of the desirable that influence the ways people select actions and evaluate events.
698 They are involved in judgment and decision making in design. They may furthermore be
699 specific to social groups and cultures (Détienne et al., 2019; Le Bail, 2020). Our findings show
700 that the proposed resources share knowledge held by diverse stakeholders scattered across the
701 country, with diverse expertise (e.g. farmers, advisors, teachers), and beliefs. We consequently
702 sometimes found divergence over values; for instance, when the facilitator proposed resources
703 including both till and no-till alternative solutions (G2, Table 2), some designers considered
704 only no-till techniques as valuable, since they fully supported conservation agriculture (and its
705 principle of no soil tillage). In view of our findings, we consider that the value-laden nature of
706 resources may expand the design space (i.e. the space of possibilities) as it provides knowledge
707 which is not in the designers' initial base. On the other hand, it may hamper its widespread use,
708 when the designer is strictly opposed to the value embedded in the knowledge. This raises
709 questions on how to implement the G2 guideline depending on the context of use, e.g. with
710 more or less tensions between specific social groups. The facilitator's role could also be
711 decisive in favoring enlargement and controlling impediments to the use of such resources
712 during design process. Similarly, the use of knowledge that was not fully stabilized was
713 controversial. Some designers did not consider knowledge derived from a single farmer-
714 innovation as stable (G2, Table 2), because it did not derive from the statistically-proven results

715 of R&D trials, whereas others saw it as generative knowledge that inspired design. Today, in
716 the aim to support farmers to invent and to implement agroecological systems, advisors have to
717 develop new skills to become facilitators and innovation brokers (Compagnone et al., 2018;
718 Klerkx et al., 2012a), allowing to face situations they now have to cope with (Cerf et al., 2011).

719 Moreover, as the information sought by designers is sometimes described in terms that
720 differ from those used in the resources, its access may be limited. It is therefore important to
721 facilitate knowledge sharing by adopting a common vocabulary, accessible to everyone, using
722 clear and readily comprehensible language to describe designers' decisions (Karsenty, 2001).
723 In this sense, we propose some recommendations to describe the functions in the FBR and the
724 BBR (e.g. starting with a verb).

725 More generally, it is clear that the knowledge-structured resources are not self-sufficient. It
726 is essential for the facilitators of design workshops to strongly support their use (e.g.
727 reformulate functions, change modes of representation, and manage conflicts over values). In
728 this sense, such cognitive resources are only parts of the Agricultural Knowledge and
729 Information Systems (AKIS), which aims to share various type of knowledge, know-how, and
730 participatory research in the view to promote the innovative design of agroecological systems
731 (Klerkx et al., 2012b).

732 4.2.2 *Questioning the dichotomy between designer-users and contributors*

733 Lastly, to open some perspectives, such knowledge-based resources question the
734 dichotomy between designer-users and contributors. In our study, user tests with designers
735 (using the knowledge-based resources) or contributors (enhancing the resources with new
736 knowledge) were carried out separately. Regarding the elaboration of the cognitive resources,
737 our findings showed that the involvement of various contributors with diverse expertise
738 (farmers, advisors and researchers, in our case studies), renews and reviews the collective
739 production of the knowledge-structured resources. We also showed that contributors not
740 involved in the design project helped to review resources previously developed by others, as
741 promoted by Karsenty (2001, 1996), for instance to better understand and characterize the
742 described solution in EBR, and unravel systemic interactions. Moreover, contributors were
743 sometimes also designers themselves, or had already supported design processes. They
744 observed and interpreted the results of their actions, that is, the implementation of designed
745 objects (e.g. farming practices, cropping systems). As owners of situated knowledge, they
746 expressed their difficulty in identifying, formulating and structuring knowledge in both

747 individual and collective sessions of resource production (e.g. especially experiential
748 knowledge from the implementation of complex cropping systems in the field). We thus
749 conclude that the more the contributors participate in design activities, the more they can
750 identify, filter and formulate relevant knowledge for design, while anticipating the reuse of the
751 resources. The use of the cognitive resources in design situations proved to be a useful way to
752 procure feedback, thus feeding by action the collective and iterative design of resources
753 (Lacoste and Powles, 2016) - referred to as the reflective conversation described by Schön
754 (1992).

755 It may therefore be interesting to bring designers and contributors together in training
756 sessions to share knowledge and to build such cognitive resources that mix scientific-based and
757 experience-based knowledge. Online platforms gathering a diversity of outputs, from
758 experiences to technical drawings (Salembier et al., 2020), could support these interactions.
759 The remaining challenge is to stimulate and facilitate the extensive sharing of such knowledge-
760 structured resources among designers and facilitators, to support their design process or design-
761 support activities, and to involve and support contributors in the collective elaboration of these
762 resources over time (improvement loop). Further research could focus on analyzing the
763 interactions between members within a community of practices, and between several
764 communities, and their commitment to collective elaboration of cognitive resources. One
765 question remains, regarding the impact of the increased use of social media and the rise of
766 Internet, affecting these interactions, including farmers or advisors who share past experiences
767 on online forums (M. Prost et al., 2017).

768 ***Conclusion***

769 This study is based on a user-centered approach to elaborate knowledge-structured
770 resources for the purpose of supporting divergent and convergent thinking within an exploration
771 process: the function-based resource, the biology-based-resource, and the experience-based
772 resource. We shed light on how these cognitive resources were used in design workshops:
773 designers exploring alternatives, facilitators managing the exploration process within design
774 workshops, and support contributors (i.e. experimenters) capitalizing on action-based
775 knowledge. This work aimed at stimulating collective elaboration of standardized cognitive
776 resources to: (i) widely share situated and generic knowledge; (ii) value farmers' experiences,
777 in a way that enhances their take-up by other farmers-designers, as powerful sources of ideas
778 and opportunities; and (iii) support production of design-support resources to stimulate the

779 redesign of farming systems. A remaining challenge is to support the collective production over
780 time of such knowledge-structured resources, and the development and maintenance of resilient
781 communities of stakeholders (both designers and contributors) with diverse expectations and
782 values, motivated by a common goal of designing agro-ecosystems for agroecology. These
783 results open avenues for further research on socio-organizational conditions to support the
784 establishment of such communities of designers and contributors, capitalizing on diverse types
785 of knowledge, and collectively using such resources in the design of agroecological cropping
786 systems.

787 *Acknowledgements*

788 We thank all our colleagues involved in this research, and are deeply grateful to all the
789 participants of the prototype tests. We also thank the reviewers for their feedback that helped
790 us to improve the manuscript. We finally thank Liz Carrey Libbrecht for reviewing the English
791 version of this paper.

792 This work was funded by the University Paris-Saclay, and by the national action plan Ecophyto
793 (project FORCOCO). It was carried out under the umbrella of the Initiative for Design in
794 Agrifood Systems (IDEAS).

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