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1 A new method to co-design agricultural systems at 2 the territorial scale - Application to reduce herbicide 3 pollution in Martinique

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15 game, sociotechnical diagnosis

16 1 Introduction

17 Since the Second World War, intensive agriculture has been responsible for negative externalities
18 which affect the environment through excessive use of chemical inputs. Chronic environmental
19 pollution is one of the most symptomatic examples of such negative externalities. To face this
20 challenge, an agroecological transition of food systems is clearly required (Wittmayer et al., 2014). A
21 shift towards agroecology requires three elements to be taken into consideration: (i) the characteristics
22 of highly spatialized biophysical and ecological phenomena at a far bigger scale than that of the plot;
23 (ii) the actions of all the actors who influence these phenomena, not only farmers but also other actors
24 of the territory; and (iii) and interactions between farmers and the territory (Benoit et al., 2012;
25 Leenhardt et al., 2015; Veldkamp et al., 2001). From this point of view, increasing research considers
26 territory as an object that needs to be designed in collaboration with the actors (Lardon et al., 2017).
27 Concerning the design process, according to Prost et al. (2017), the complexity of territories makes it
28 very difficult to establish *a priori* a precise definition of the object to be designed. However, a
29 definition can be reached when a wide range of stakeholders take part in a collective design process
30 that combines diverse forms of knowledge.

31 The design objectives in agricultural sciences have evolved in recent years in parallel with the growing
32 role of territorial design (Prost et al., 2017). Accordingly, new design methods are also evolving,
33 including the recent development of methods for the design of complex agricultural systems. These
34 systems are made of : 1) the agroecological entities at different organisation levels (such as fields,

35 farms, rivers, natural habitats, etc.), with the organized set of laws, rules and choices involved in their
36 structure and functioning (Osty 1994); and 2) the actors involved in their management such as the
37 farmers, and the other stakeholders of the territories and food systems (Doré et al., 2006). Examples of
38 methods include serious games used for the design of a territorial project (Lardon et al., 2017);
39 structured design approaches to design a sustainable agricultural sector and an agroecological park
40 (Elzen and Bos, 2019; Romera et al., 2020); and innovative design approaches to design an agro-
41 ecosystem (Berthet et al., 2016a). These methods are built on close dialogue between practitioners and
42 scientists on the knowledge, know-how and solutions that already exist or which are needed to remove
43 any obstacles from the paths of innovation, rather than the operational application of scientific
44 discoveries (Meynard et al., 2012; Prost et al., 2017).

45 Because sustainable agricultural systems require a break with current production paradigms, and given
46 its potential, innovative design merits further development at the territorial scale (Meynard et al.,
47 2012). The C-K theory, developed in the industrial world to conceptually model participatory design
48 reasoning, formalised the innovative design approach we used for this study (Hatchuel and Weil,
49 2003; Le Masson et al., 2011). The innovative design approach is iterative, allowing ongoing
50 modification of the desired object, changes in the skills required, in the method of evaluation, the
51 knowledge to be applied, and the mode of collaboration (Le Masson et al., 2014; Meynard et al.,
52 2012). Recent studies have sought to adapt the innovative design approach to the agricultural plot
53 (Berthet et al., 2016; Leclère et al., 2018; Ravier et al., 2018) and have made it possible to consider the
54 territory as an object to be designed.

55 Innovative design methods lack the analysis of path dependencies and lock-in to innovation in a
56 formal way. Nevertheless, both are required to identify the actors to involve as well as the cognitive
57 biases that each actor will bring to the innovation process. Moreover, the evaluation of solutions in
58 real situations is not generally carried out on objects as complex as a territory, while the process of
59 designing innovations continues in their use. Berthet et al., (2016), after a comparative critical analysis
60 of different design methods (including innovative design and serious gaming), recommend to use them
61 in a combined way. Following their recommendation, we built a new method based on innovative
62 design, combined with an analysis of the sociotechnical lock-in of the studied territory and with a
63 serious game to get closer to the operational conditions experienced by the actors.

64 Our method was developed as part of a program to reduce the pollution of river water in Martinique
65 caused by excessive use of agricultural herbicides. The method aims to identify radically new
66 solutions at a scale at which it is very difficult to define objectives and performance criteria for each
67 actor, since pollution of rivers by herbicides is subject to complex dynamics in space and time (Mottes
68 et al, 2017). The paper is organised as follows: After describing the study site, we present the

69 conceptual framework of the method and its implementation at the study site in four steps. We then
70 present and discuss the results we obtained by applying the method and the scenarios.

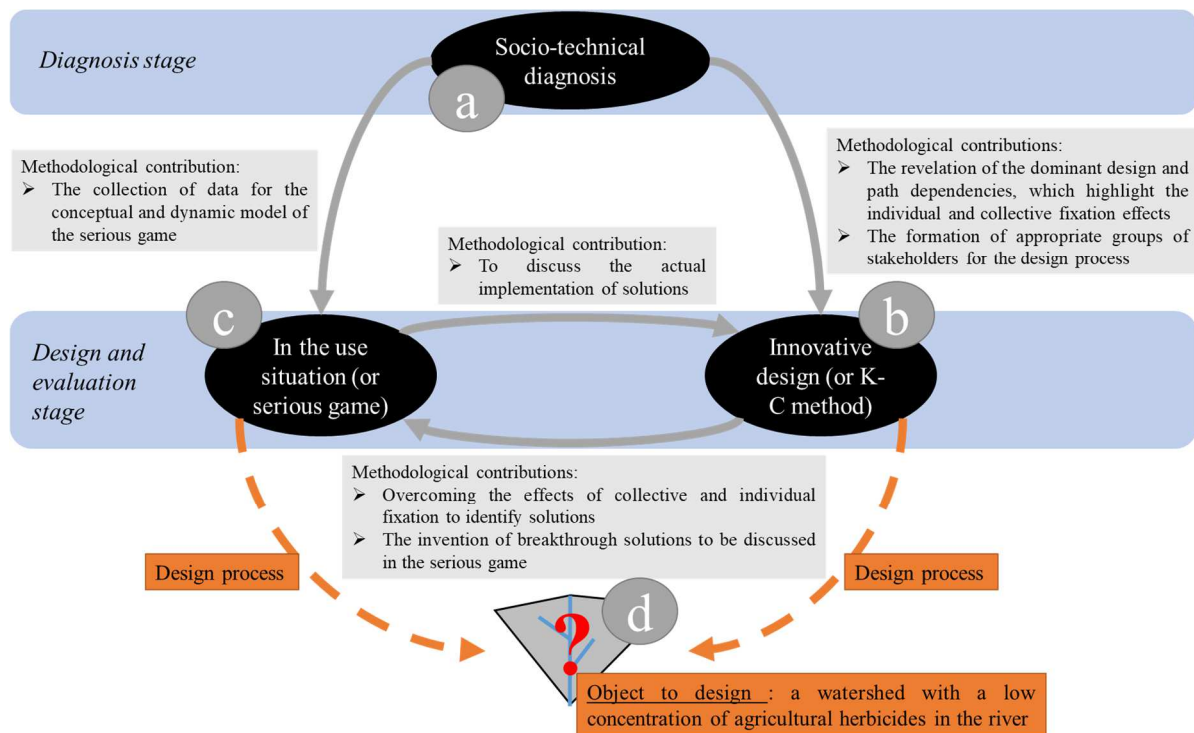
71 2 Materials and Method

72 2.1 Study area

73 To create and test this method, we chose the Galion River watershed in Martinique (French West
74 Indies) where the river is polluted by herbicides. This watershed covers 45 km², and the three main
75 farming systems in Martinique are practiced there: sugar cane monocropping (*Saccharum officinarum*)
76 (35% of agricultural land, 38 farms, 370 ha); banana monocropping (*Musa* spp.) (45% of agricultural
77 land, 21 farms, 500 ha); and market gardening and food diversification (yam, tomatoes, salad, fruit,
78 etc., 20% of agricultural land, 82 farms, 130 ha). Galion watershed includes a water quality monitoring
79 system that has assessed the pesticide content of river water at weekly intervals since 2016 (Mottes et
80 al., 2019). The major pollutants identified are chlordecone, herbicides and post-harvest banana
81 fungicides; see Anckaert et Mottes (2019) (in French) for a complete list of the ~400 active ingredients
82 assessed.

83 2.2 Conceptual framework of the method

84 Three methods were combined to build our method that meets new design needs in agronomy, i.e., a
85 territorial scale approach that goes beyond the limited exploration of solutions. Our method combines
86 a sociotechnical diagnosis (Fig1a) to identify the problem, use of the C-K method (Fig.1b) to open the
87 path to possible innovations, and a serious game (Fig.1c) to refine and assess the innovations. With
88 our method, the results are not known in advance (Fig. 1, d), it predicts the main properties of the
89 object we want to design, in our case, a watershed with low concentrations of agricultural herbicides in
90 the river.



91

92 *Figure 1: Conceptual diagram of our method which combines three methods. The grey boxes show the*
 93 *theoretical contribution of one method to another (a, b, c) (arrows). The whole method aims to design*
 94 *new watershed management (d).*

95 2.2.1 Sociotechnical diagnosis

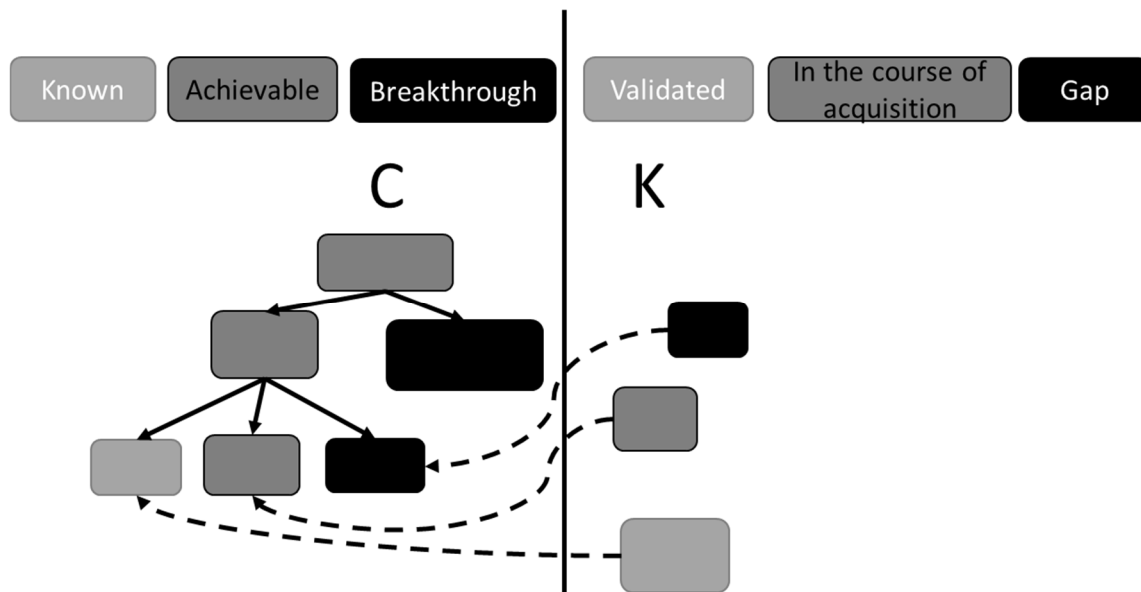
96 Agronomists maintain that a diagnosis is essential for the implementation of any design process (Doré
 97 et al., 1997; Meynard et al., 2001). A diagnosis makes it possible to: (1) build a shared vision of the
 98 concept before starting the process; (2) identify the actors to be associated with the process and the
 99 lock-in that characterises their innovation processes; and (3) choose how to start the creative process.
 100 To carry out the diagnosis (Fig. 1, a) an analysis of the socio-technical system supported by the
 101 multilevel analysis of Geels, (Geels, 2004), and an analysis of path dependencies (David, 1985) were
 102 performed. These approaches help distinguish the direct and indirect actors in the innovation process,
 103 the brakes and the levers, and the central design created by the path dependencies (Geels, 2004;
 104 Loorbach, 2007). Path dependencies may be associated with fixation effects, which innovative design
 105 seeks to depart from (Ezzat, 2017). Because our aim was avoiding a path that was already too deeply
 106 entrenched to allow for innovation, in our diagnosis, we used the tools of C-K theory to identify
 107 fixation effects. To this end, we produced a C-K diagram based on the results of the diagnosis of the
 108 socio-technical system (Della Rossa et al., 2020).

109 2.2.2 Innovative design

110 To meet the requirements of creating radically new innovations for territorial design, our framework
 111 included a period of collective creativity in which the actors were removed from the context of their

112 usual practices. The driving force of our method is innovative design (Fig. 1, b), based on the theory of
113 design called the C-K theory (Hatchuel and Weil, 2003; Le Masson et al., 2014). The C-K theory
114 represents a design process as the interaction between and the co-evolution of two spaces, concepts, or
115 ideas (C) and knowledge (K). A concept is an undecidable proposition, meaning it is neither true nor
116 false, unlike knowledge of space K. When a concept of space C becomes decidable, it integrates space
117 K and the design process is a success (Le Masson et al., 2014). For breakthrough innovations, it is
118 necessary to enter original ideas in space C. This in turn requires modifying the definition of the object
119 by adding unexpected characteristics to an initial concept (called C0), which instantiate the object to
120 be designed (Agogu e et al., 2014).

121 A standard C-K diagram is a conceptual representation of a design reasoning based on the C-K theory,
122 in two spaces K (knowledge space) and C (concept space) (Fig. 2). In the C space, a *known concept*
123 refers to a set of known and well characterised technical solutions that already exist, an *achievable*
124 *concept* needs to be deepened to exist, and a *breakthrough concept* is far from the dominant design of
125 the actors and usually does not yet exist (Agogu e et al., 2014). These three types of concepts are
126 summarised in a C-tree, structured horizontally from the least disruptive concept to the most disruptive
127 concept with respect to the dominant design (Fig. 2). The C-tree partitions are inclusive, i.e. a sub-
128 concept is included in its superior concept. A sub-concept highlights a characteristic of the superior
129 concept. For example, if the superior concept is "a coffee cup", the sub-concepts may be the number of
130 handles on the coffee cup. The concepts are linked to knowledge in the K space. The K space gathers
131 knowledge which is more or less acquired and the knowledge that is lacking used to develop the
132 concepts of the C space. The K space is organised as follows: *validated knowledge* is knowledge that
133 is already acquired, often (but not only) knowledge of *known concepts*. *Knowledge in the course of*
134 *acquisition* is the subject of dedicated research programmes, often (but not only) concerning
135 *achievable concepts*. Finally, a *knowledge gap* refers to knowledge that is missing or not operable by
136 the actors involved, often (but not only) concerning *breakthrough concepts* (Agogu e et al., 2014).



137

138 *Figure 2: Simplified C-K diagram. In space C, we position known concepts (on the left, light grey),*
 139 *achievable (grey) or breakthrough (on the right, black), connected by dashed arrows with knowledge*
 140 *of space K: validated, in the course of acquisition, or identified as a knowledge gap (this colour code*
 141 *is used throughout the paper).*

142 The innovative design theory was transformed into a method called KCP because of the order of the
 143 stages (Knowledge, Conception, Proposals) (Hatchuel et al., 2009) applied in agronomy (Berthet et al.,
 144 2016; Leclère et al., 2018; Ravier et al., 2018). Our study focuses on the stages of the method that
 145 make it possible to explore new ideas without fixation effects. According to Ezzat (2017), fixation
 146 effects are cognitive biases that prevent people from considering innovations that are radically
 147 different from what they already know. We discuss the stages of the KC method we selected from the
 148 KCP method (Knowledge and Conception) in the rest of the article.

149 2.2.3 In the use situation (serious game)

150 This method seeks to check whether the innovations designed by the actors “during workshops” fit the
 151 social and biotechnical systems of the territory under study and meet the end users’ expectations (Fig.
 152 1c). There are two reasons for checking. The first reason is that the innovation process continues after
 153 innovation is applied (Cerf et al., 2012). Observing changes in the object while it is “in use” is
 154 therefore crucial to assess whether it is operational. The second reason for checking how the
 155 breakthrough innovations fit is to assess their effects on the problem to be solved (in our case,
 156 herbicide pollution of a river). Both objectives are difficult to test in a territory in real life, because (i)
 157 the innovations are breakthroughs, consequently no references are available, (ii) pollution is the result
 158 of individual and collective actions on the common object, and (iii) the full-scale process can take a
 159 long time to complete. To at least partially, get around these difficulties, we filled the gaps via “design
 160 during use” (Fig. 1, c), (Cerf et al., 2012; Ravier et al., 2018). In other words, we simulated the use of

161 innovations in the territory by means of a serious game which provides a secure space to test solutions
162 (outside reality) and allows new knowledge to be created thanks to interactions between innovations
163 and systems (Souchère et al., 2010). Our serious game was based on the WATPPASS computer model
164 (Mottes et al., 2015) used to model pesticide flows to the river. This serious game allowed us to
165 understand how the actors could collectively implement and adapt the innovations during their use (in
166 this case, simulated use), and then to evaluate the reduction in the use of the herbicides and the
167 potential reduction in pollution of the river that would result. The literature on the subject offers many
168 examples of a game combining a set of rules, objects and roles that makes it possible to identify and
169 analyse the personal and collective decisions of the actors, and to evaluate the effect of their actions
170 (Moreau et al., 2019; Papazian et al., 2017; Sausse et al 2013).

171 2.3 Implementing the method in a territory

172 Table 1 summarises the procedure for implementing our new method in a territory. The four steps of
173 the method are detailed in subsections §2.3.1 to §2.3.4. The research team was in charge of building
174 the methods to help the actors build the innovations. Members of the research team were facilitators
175 during the workshops.

176 Table 1: The four steps in the design process, in relation to the method, the designers (who actively
177 participated in the construction of innovations), and the outputs of each step.

Steps	Method	Designers	Output
Step 1: Socio-technical diagnosis (Della Rossa et al., 2020)	Analysis of the connections between the socio-technical system and the watershed, using: <ul style="list-style-type: none"> - semi-structured interviews with the actors - review of grey literature on territorial development and agricultural development 	Research team Actors: 23 farmers in the Galion watershed and 22 actors of the farming and territorial sectors (agricultural research center, technical institutes, producer groups, water managers, state organisations, territorial agricultural innovation service)	<ul style="list-style-type: none"> - Obstacles to and levers for innovations in weed management - List of actors to get involved in the design process - Path dependencies that constrain the creativity of actors
Step 2: Drawing a standard C-K diagram	Review of result of diagnosis using C-K theory tools	Research team	C-K diagram of the standard innovation pathways used by agricultural innovation actors in Martinique: <ul style="list-style-type: none"> - the fixation effects actors share - a breakthrough path to explore with the actors
Step 3: Innovative design innovation workshops (stage K and stage C)	A participatory workshop was held to share knowledge with all the stakeholders Three participatory workshops were held to explore new ideas in small groups	Research team Actors: farmers from the three agricultural sectors in the Galion watershed (banana, sugar cane, market gardening products and vegetables), agriculture and food	Phase K <ul style="list-style-type: none"> - identifying and highlighting knowledge gaps. Emerging concepts to explore original innovations in the next phase - design groups for the following step Phase C

		research centres, technical institutes, producer groups, pesticide distributors, a water manager, state organisations, a food company	<ul style="list-style-type: none"> - new pathways explored outside the usual innovation pathways - innovations that represent a break from the dominant design - new evaluation criteria for original innovations
Step 4: Serious game to continue design during use and to evaluate the reduction in pollution resulting from these innovations	A participatory workshop including a serious computer-assisted game	<p>Research team</p> <p>Actors: farmers from the three agricultural sectors in the Galion watershed, technical institutes, producer groups, a water manager</p>	<ul style="list-style-type: none"> - discussion of the feasibility of the proposed innovations - development of original scenarios allowing varying reductions of the concentration of herbicides in Galion River

179 2.3.1. Step 1: Socio-technical Diagnosis

180 The socio-technical diagnosis conducted in Martinique consisted in interviews to identify actors linked
181 to herbicide use and water quality (Della Rossa et al., 2020). The interviews were designed to identify:
182 (1) the relations between actors within and outside their networks (business contracts, knowledge
183 exchange, these actors' representations of the roles of other actors, etc.), (2) the effects of the
184 interrelations on changes in weed management practices among farmers in the Galion watershed; and
185 (3) the obstacles to and levers for technical innovation arising from rules governing Martinique's
186 farming sector.

187 The grey literature was a source of agricultural information related to the three objects we were
188 investigating: supply chains (Evaluation of Sustainable Banana Plan 1, Specifications of certification
189 in supply chains such as GlobalGap, AOC rum, Organic Agriculture, supply chain contracts); farmers
190 (technical documentation provided by the supply chain on agricultural systems in Martinique, thematic
191 files on agriculture in Martinique for each sector); and territory (programmes and guidelines for
192 agricultural development promoted by the State, European Development Programmes for the
193 outermost regions of the European Union, water quality information, Galion River contract,
194 urbanisation plans, Natural Parks Charter) (Della Rossa et al., 2020).

195 To identify obstacles to reducing the use of herbicides in agriculture in Martinique, we combined
196 sociotechnical and territorial conceptual frameworks in a grid, which we then used to highlight the
197 elements of the socio-technical system defined by Geels (2004), the rules, the actors, and the artifacts
198 (Della Rossa et al., 2020). According to Geels (Geels, 2004), rules and regimes provide stability by
199 guiding the perceptions and actions of the actors, which prevents them from proposing innovations
200 that differ too much from these rules. What is more, these actors belong to organisations that are
201 trapped in networks of interdependence that reduce possibilities for change. Finally, material artefacts
202 imply relationships of complementarity and economic dependencies with other systems, and
203 depreciation costs that further reduce possibilities for change, especially radical change (Cowan and
204 Gunby, 1996). Identifying these different elements enables us to understand what drives innovation, as
205 well as what prevents radical innovations from emerging in the existing socio-technical regimes.
206 However, Geels limited his analysis to production systems, whereas our innovations concern a
207 territorial system, itself composed of rules, actors, and artefacts in its three dimensions (material,
208 organisational and conceptual (Laganier et al., 2002)) which may represent obstacles to radical
209 innovation. This is why we added the identification of these elements to those of the socio-technical
210 system usually considered in transition theories.

211

2.3.2. Step 2: Drawing the standard C-K diagram

A standard C-K diagram is a map of the state-of-the-art related to the object to be designed. It shows explored and unexplored innovation pathways, and the positions of existing innovation projects as well as those likely to emerge (Agogu  et al., 2014; Hatchuel and Weil, 2003). It makes it possible to review conventional design pathways by proposing possible expansions (Agogu  et al., 2014). This tool is used to increase the actors' innovation capacities.

For example, figure 3 presents a possible standard C-K diagram to design a coffee cup.

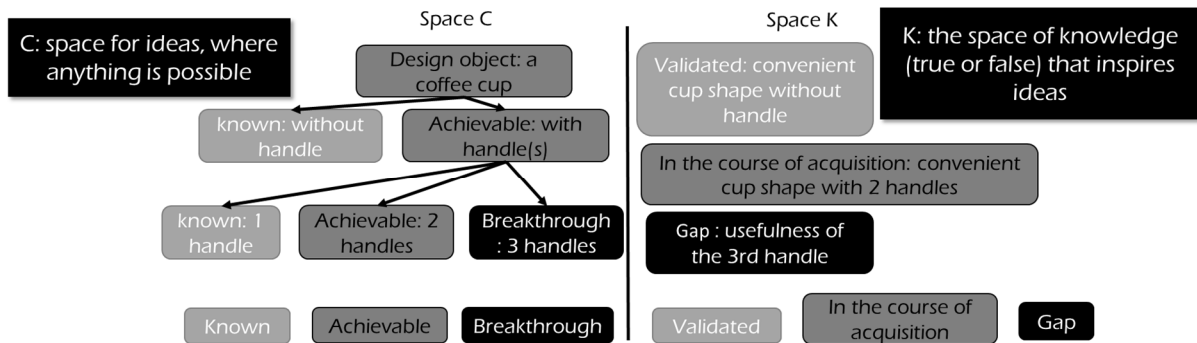


Figure 3: Example of a standard C-K diagram for the conception of a coffee cup. Space C contains known concepts (on the left, in light grey), achievable (grey) or breakthrough (on the right, black), and space K contains the knowledge that inspired the different versions, validated (in light grey), in the course of acquisition (grey) and knowledge gap (black)

In this example (Figure 3), we start the design by the number of handles the future coffee cup will have. In this case, the known concept is a bowl, i.e., a cup with no handle, based on knowledge of the shape of coffee cups with no handles (i.e. bowls) in shops. One possible achievable concept, meaning an existing idea but which requires further study, is a cup with one or more handles, a concept that we develop further depending on the number of handles. The next known concept is a cup with one handle, an achievable concept is a cup with two handles, and a breakthrough concept would be a cup with three handles, related to a gap of knowledge about the usefulness of this third handle in a funny way. With this simple example, the construction of a standard C-K diagram becomes clear: a dominant design for a coffee bowl with no handle, or for a cup with one handle, and the breakthrough, a coffee cup with three handles.

To start our real C-K diagram, we inserted the original concept (C0) we wanted to design: a watershed with a low concentration of agricultural herbicides in the river. Before drawing the C-K diagram, we have investigated the innovations currently under development, distinguishing between common, ignored and discarded properties, we analysed the history of the development of the innovations, the knowledge used to create the innovations, and finally we distinguished the degree of disruption of the innovations using the Hill and MacRae grid (Hill and MacRae, 1996). We identified which actor was

240 involved in the development of each innovation, each actor's objectives and the formal and informal
241 relationships between the actors, their agreements, and disagreements.

242 Following this method described below, the research team drew a standard C-K diagram by replacing
243 the information collected in the diagnosis in Step 1. We then identified shared fixation effects with
244 series of known concepts (Agogu  et al., 2014). We used this information to encourage the facilitators
245 of the design workshops, not to suggest innovations, but to steer the participants away from the
246 pathways they are used to following.

247 Finally, we used this standard C-K diagram, particularly the most disruptive concepts, to start the
248 creative design workshops described below.

249 2.3.3. Step 3: Innovative design workshops (stages K and C)

250 In this step, we alternated knowledge exchange sessions (Stage K) and groups of guided creativity
251 (Stage C), based on studies that used the innovative design method (Ravier et al., 2018, Berthet et al.
252 a&b, 2016; Le Masson et al., 2014). To the workshops, we invited the actors of the territorial and the
253 agricultural sectors we had identified during the diagnosis stage who were likely to directly or
254 indirectly influence the innovation process.

255 The aim of the K stage was to build a knowledge base which challenges received ideas and fixed
256 definitions of objects, while creating common cognitive ground that is sufficiently rich to contribute to
257 the creation of new concepts. Workshop K was designed to overcome the participants' fixation effects.
258 At the beginning of the workshop, the research team presented the dominant design they had inferred
259 from the diagnosis. This was followed by presentations by experts aimed at encouraging reflection
260 among the participants beyond the effects of fixation. Although the dominant design was presented to
261 the workshop participants, it was not specifically discussed with them, because the focus of the
262 workshops was on overcoming the fixation effects. In their presentations, the experts presented
263 existing knowledge as well as existing problematic issues on the topic of processes of herbicide
264 transfer and river pollution, design processes at territorial scale, and agricultural weed management in
265 Martinique. The presentations made during workshop K are listed in table 2.

266 Table 2: Topics of the talks given by experts during the K workshop

Themes related to the object to be designed	Presentation
Transfer processes and the resulting herbicide pollution	Mechanisms of pesticide transfer at the watershed scale
The territory considered at the watershed scale	Shift towards more sustainable systems and the possibility for innovation combining production and value chains
Weed management by farmers	Response of soil macrofauna to the transition to organic farming

	innovative techniques for managing grass cover in the plot: cover crops and association with animals in orchards, plant cover in banana plantations, diversified agricultural techniques according to the type of crop
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267

268 The experts' presentations were discussed with 26 participants (for a list of participants see
 269 "designers' column" in Table 1) and at the end of the K stage the research team was able to identify
 270 the new knowledge contributed by the experts and the other participants, and their collective's
 271 knowledge gaps.

272 The design step C is creative, and was facilitated by "projector concepts" based on analysis of the K
 273 stage. The aim of these concepts is to stimulate exploration of paths that depart from the dominant
 274 design. For example, as projector concept, we used "the agricultural sector of Galion watershed". This
 275 concept did not exist in the representations of the local stakeholders. Moreover, in Martinique, the
 276 main sectors are associated with only one crop and rarely include the territorial scale in their
 277 perception of development (Della Rossa et al. 2020). By associating the term "sector" with an
 278 environmental object "watershed", we encouraged the emergence of new forms of evaluating
 279 production in the watershed. Discussion took place in small groups and the composition of each group
 280 was decided based on the skills and knowledge of the participants that were relevant for the projector
 281 concept. The workshops were transcribed to capture any new ideas that arose from the discussions
 282 between participants. The research team then compared these ideas with the dominant design to
 283 establish the degree of disruption.

284 During these C-workshops, 15 participants (see Table 1) put forward their ideas related to the
 285 projector concept. To maximize the potential for creativity without fixation effects, the facilitator of
 286 the workshops was aware of the fixation effects, and redirected the discussion when it reached the
 287 previously identified (see 2.3.2). This guided the actors, including implicitly, towards different
 288 reasoning with the help of provocative examples and questions that deepened some of the concepts, or
 289 by emphasizing an original idea that came up during the think tank of these C-workshops, for example
 290 "what if the land did not belong to anyone?".

291 At the end of the K and C workshops, we were able to complete the standard C-K diagram and assess
 292 whether the K and C workshops had enabled us to deepen the breakthrough pathway. The process also
 293 informed us about the actors' expectations of the object under design and the additional criteria to
 294 evaluate it. An additional criterion is a criterion to evaluate the designed object that participants add
 295 during the design process. These new criteria completed the K space of the standard C-K diagram by
 296 helping define the object to be designed.

2.3.4. Step 4: Serious game to enable continuing design during virtual use and to evaluate pollution

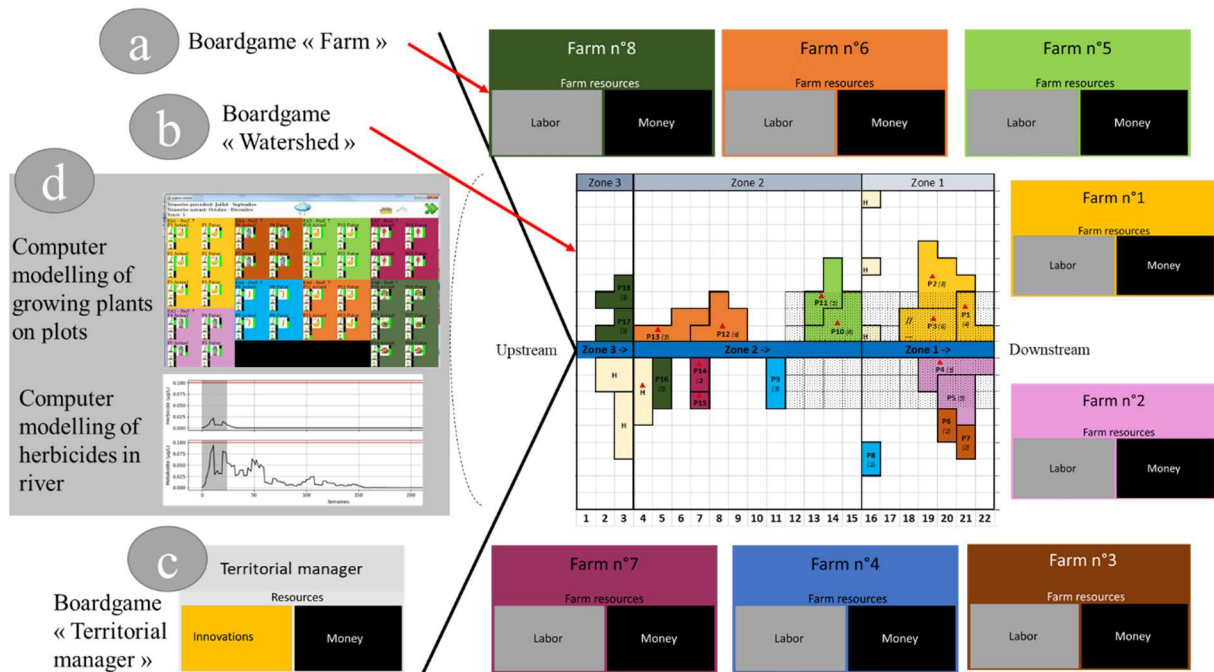
For this design step, we were inspired by the tools used in the companion modeling method (Etienne, 2011). We first conceptually modeled the system under study using the ARDI method (Actors, Resources, Dynamics and Interactions) (Etienne et al., 2011) with data from the socio-technical system, and applied the conceptual model in a serious game, assisted by computer. The level of pollution was calculated from a validated pollutant transfer model validated and with data presented in (Mottes et al., 2015, Mottes 2013, Bizien, M. 2018).

The model of the WATPPASS-Game is based on two modules, an agronomic module and a pesticide transfer module.

The agronomic module simulates the development and growth of the crop and weeds in an integrated and qualitative manner (4 different stages defined by height and leaf area index) as well as competition for light in the plot using the Beer Lambert law (Mottes 2013). The time step of this module is three months, which was selected as a good compromise between precision and operability in the design of the scenario at the watershed scale. Location, season, competition for light, and agricultural practices are the factors that influence the growth of crops, weeds, or both. Players update their decision concerning the practices every three months.

The pesticide transfer model uses a metamodeling approach (3 480 000 total runs) to assess the amount of herbicides exported from the plot through runoff and leaching for a period of 30 years after each pesticide application. To do so, 5 800 application conditions on the watershed (soil, place, type of crop, crop stage, weed cover, application equipment, position of application, etc.) were simulated 600 times each at a random time step to obtain average emission curves for runoff and leaching (Bizien 2018) in the different situations. Each time a herbicide is applied in the watershed, depending on the location of application, the season and the type of soil (sensitive factors according to Bizien (2018)), the module selects the appropriate 30-year emission curve and sends it to the watershed system which routes it to the outlet. Routing depends on the distance between the plot and the river system in the watershed according to the formalism described by Mottes et al. 2015 adapted to the situation of the Galion watershed. The quantity of pollution at the outlet are then broken down into a weekly time step. The principle of the game was as follows (Fig. 4): the farmer-players (Fig. 4, a) had to control the weeds growing on their own farm, which is located in the watershed (Fig. 4, b), and to choose innovations (designed during the KC workshops) to implement, given the financial and labour resources available to them. A territorial manager-player (Fig. 4, c) had additional resources to support the implementation of these innovations, or not. The agricultural sectors were representative of those of the players who participated in the KC workshops and among the farmer-players who took part in the serious game (see Table 1). The game was assisted by a computer model inspired by (Mottes et al.,

332 2015) and (Mottes 2013) to connect weed management practices and river pollution. The computer-
 333 assisted game (Fig. 4, d) made it possible to assess the effects of players' actions on crop and weed
 334 dynamics, and on herbicide pollution of the river in real time. The land use in the game is
 335 representative of the real land use in the Galion watershed. All we did was to group several farms of
 336 the same type to use 8 players instead of 141 farmers.



337
 338 *Figure 4: Diagram of the organisation of the serious game. Farmer-players have resources on their*
 339 *farm (a). The plots are located in the study watershed (b). A territorial manager-player (c) discusses*
 340 *the conditions for implementing the innovations with the farmer-players. The players make their*
 341 *decisions based on the growth stage of the plants and weeds in their plots, and on the level of*
 342 *herbicide pollution of the river computed in real time (calculator inspired by Mottes et al. (2015) (d))*

343 At the beginning of the game, we let the farmer-players play with no advice and no innovation, river
 344 pollution is set at zero to establish the starting situation of pollution. When an herbicide pollution peak
 345 in the river was announced, all the players started discussing implementing innovations to solve the
 346 problem.

347 The entire workshop was filmed, and the games including the players' moves were entirely recorded. It
 348 was therefore possible to study both the individual and collective behaviour of the players, changes in
 349 their farming resources over the course of the game, as well as to replay certain actions with the model
 350 to isolate the impact of an action or set of actions on the level of pollution of the river. We then
 351 analysed the data concerning the individual and collective actions of the players, and distinguished
 352 three scenarios of agricultural organisation of the watershed. The scenarios correspond to different
 353 associations of collective innovations chosen by the players who formed groups with a specific
 354 function and produced specific results with respect to river pollution. We then analysed these

355 scenarios from the point of view of water pollution and using the new evaluation criteria identified in
356 the K and C stages.

357 In the game, we chose not to provide information on the respective responsibilities of the farms in
358 river pollution, so as not to turn the game into the usual dead-end debate. We assumed that without
359 any assistance with interpretation, the actors would become more aware of their representation of the
360 responsibility of banana farming, thus breaking the collective dynamic. Our hypothesis is consistent
361 with the statements of Kellon and Arvai (2011), where preferred alternatives pre-exist among the
362 actors of a decision-making process concerning natural resources, and the facilitators are responsible
363 for building informed and defensible alternatives with the actors.

364 Finally, we analysed the results of the method with respect to the relevance of the combination of the
365 three theoretical and methodological frameworks for our design objectives: changes in the territorial
366 object; breaking away from the dominant design, the innovations imagined by the actors; and the
367 potential implementation of these innovations in real life.

368 3. Results

369 3.1. From the identification of path dependencies to the 370 standard C-K diagram, the starting point for design

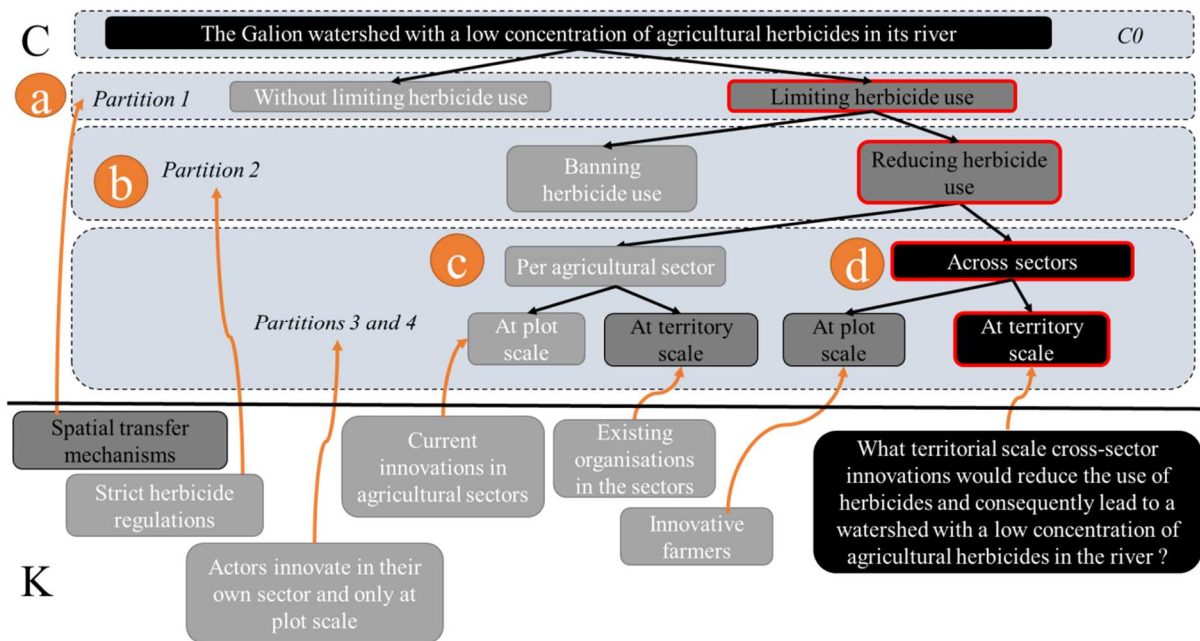
371 The diagnosis showed that all the agricultural sectors (sugar cane, banana, and diversification crops)
372 have specific path dependencies but share the one that considers innovations only at the scale of the
373 plot (Della Rossa et al., 2020).

374 The production objectives are specific to each sector. The banana sector wants to move towards an
375 agroecological system that preserves the monocultural system. As a result, it selects weed
376 management innovations aligned with that choice (such as associating banana with non-marketable
377 cover crops). The sugar cane sector also wants to continue its monocultural system, and stay close to
378 the sugar factories, in addition to not challenging mechanised harvesting. This attitude reduces the
379 possibilities for innovations in weed management by almost only searching for (1) mechanical
380 solutions that are consistent with mechanised harvest, or (2) varietal improvement. The agricultural
381 diversification sector wants to move towards strong agroecology, with significant degrees of
382 diversification at the plot and farm scale (with weed control practices that are mainly manual or that
383 involve crop combinations, or even crop / livestock combinations).

384 We also found that the agricultural sectors are structured independently of each other, and almost
385 never interact (Deffontaines et al., 2020; Della Rossa et al., 2020). They also have preconceived ideas
386 about other sectors, in particular farmers in the sugarcane and diversified agriculture sectors, who
387 think herbicide pollution in river is mainly the fault of the banana sector. In fact, each agricultural

388 sector have its own Research & Development and supply chain actors, but different degrees of
 389 financial and material resources. The motivation of all three agricultural sectors in reducing their use
 390 of herbicides is not connected with a desire to reduce river pollution, or to foresee future regulations
 391 (banana and sugar cane growers), or to reduce the health risk for farmers (diversification). Technical
 392 assistance is available to banana farmers thanks to the strong vertical structure of the sector around a
 393 central actor that conducts active agricultural research and provides advice. Less assistance is available
 394 for sugar cane, especially for small-scale farmers, as the central actor has limited capacity to structure
 395 the sector and no funds for innovative research and advisory services. Finally, the diversified farming
 396 system sector has few financial and material resources, with 20% of the farmers divided between six
 397 producer organisations. Research and development, mainly represented by the chamber of agriculture,
 398 has difficulty in identifying innovations to respond to the wide range of existing situations.

399 Agricultural and territorial development programmes remain based on the objectives and drivers of
 400 innovation defined within each agricultural sector, because public authorities delegate the task of
 401 deciding on the guidelines and rules for funding these programmes to the main stakeholders of each
 402 sector. Thus, the scale of the watershed does not exist in agricultural innovation processes, particularly
 403 weed management. This implies that the issue of “water quality” (here of the Galion River) receives
 404 scant attention in the sector’s innovation approaches. The agricultural sectors in Martinique have two
 405 strong path dependencies that influence their dominant design: (i) they innovate within their own
 406 agricultural sector; and (ii) they innovate mainly at the plot scale, with very little consideration for the
 407 territorial scale.



408

409 *Figure 5: Standard C-K diagram resulting from the socio-technical diagnosis. The boxes use the same*
 410 *colour code as that defined in Fig. 2: known concepts (light grey), achievable (grey) or breakthrough*

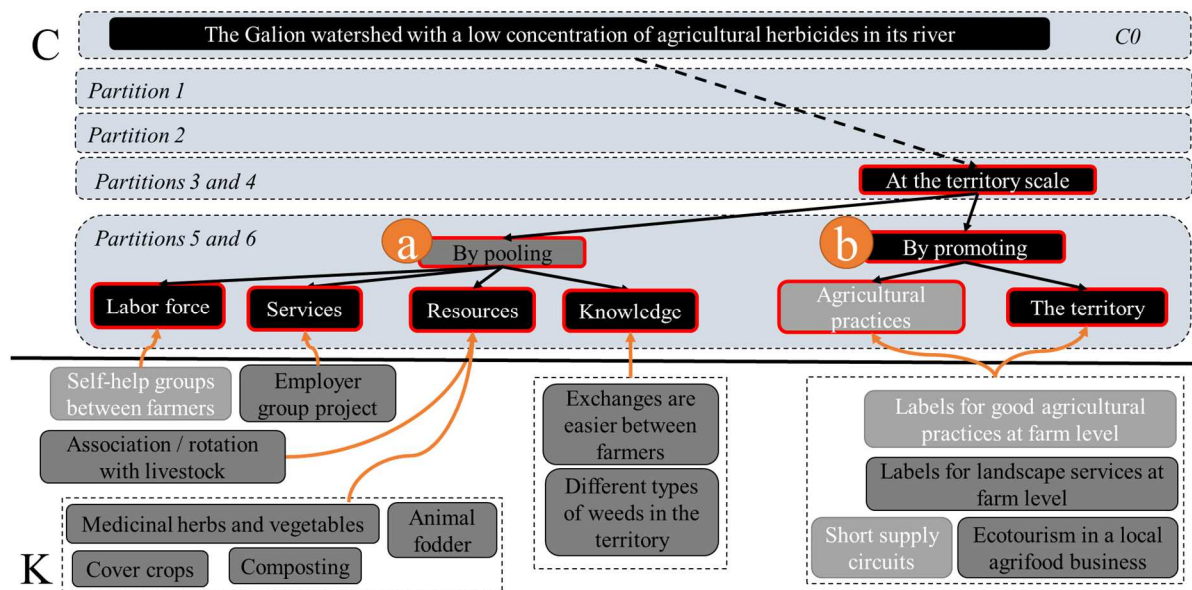
411 *(black). Arrows identify knowledge related to its corresponding concept. The boxes outlined in red in*
412 *the C space represent a departure from the path of innovation from the collective fixation effects of*
413 *actors of innovation in weed management in Martinique. The letters "a", "b", "c", "d" locate the*
414 *elements of the figure described in the text.*

415 Based on the previous socio-technical diagnosis, the research team built the standard C-K diagram
416 shown in Fig5. The partitions a and b represent the context of rules in which the actors evolve, while
417 partitions c and d are the rules produced by the actors concerned in Martinique. First, knowledge of
418 pesticide transfer mechanisms distinguished two concepts in partition 1 (Fig. 5, a). The first was to
419 reduce pollution without reducing herbicide use. Some actors, who assumed the molecules could
420 degrade before reaching the river, wanted to limit the concentration of herbicides in the river mainly
421 by creating physical barriers to slow down the flow to the river. However, most of the actors of
422 agricultural innovation in Martinique, as well as the territorial authorities, supported the second
423 concept in partition 1, i.e. reducing the use of pesticides by individual farmers. Partition 2 (Fig. 5, b)
424 concerns changes in European regulations that ban the use of an increasing numbers of herbicide
425 molecules, whereas most of the actors of agricultural innovation only wish to reduce their use.
426 Partitions 3 and 4 (Fig. 5, c and d) concern the two collective fixation effects of the actors of
427 innovation: innovation within their own agricultural sector, mainly technical innovations at plot scale.
428 This is why in partition 3, we separate the fixation effect in the concept of innovating in each
429 agricultural sector from the breakthrough concept of innovating in a cross-sector way, and in partition
430 4, we separate the fixation effect in the concept of innovating at plot scale from the breakthrough
431 concept of innovating at territorial scale. The usual trend favours the left-hand concept (Fig. 5c). When
432 this dominant design was presented to the stakeholders in workshop K, despite requests for questions
433 and comments, no participant expressed either agreement with or opposition to our conclusions.

434 The building of the standard C-K diagram made it possible for the research team to see a path
435 emerging (on the right in Fig. 5d), where the actors could innovate in across sectors at territorial scale.
436 This conceptual path represents a dramatic shift from the fixation effects of the actors of innovation in
437 weed management in Martinique. Some innovative farmers belonging to different agricultural sectors
438 who exchanged technical knowledge were already innovating in this way. Nevertheless, until now
439 there had been no innovations at the scale of the territory, across sectors, that would have reduced
440 herbicide use and consequently herbicide pollution of the river (Fig. 5, d). We therefore continued
441 along this path with the actors, in innovative co-design workshops, to try to fill the corresponding
442 knowledge gap: **What territorial scale cross-sector innovations would reduce the use of**
443 **herbicides and consequently lead to a watershed with a low concentration of agricultural**
444 **herbicides in the river?**

445 3.2. Fifteen innovative proposals emerged from the creative
 446 process

447 At the end of the K and C workshops (step 3 of the method – see above), the actors imagined 15
 448 innovations starting from two new partitions of the C-K standard diagram. Fig 5 presents the C-K
 449 diagram constructed from the characteristics and knowledge of these 15 innovations. Fig 6 is a
 450 continuation of Fig. 5 (for the sake of readability, only the additional partitions and new knowledge
 451 are included in Fig. 6)



452
 453 Figure 6: Standard C-K diagram at the end of workshops. The boxes use the colour code defined in
 454 Fig. 2. known concepts (light grey), achievable (grey) or breakthrough (black). To facilitate
 455 readability, partitions 1 to 4 are not complete here (dotted arrow), and the K space only sums up the
 456 knowledge that emerged during the workshops. Two new partitions (5 and 6) appeared in space C at
 457 the end of the workshops. The concepts framed in red are all part of the innovation pathway that is
 458 breaking the collective fixation effects in weed management in Martinique.

459 Space C in Fig 6 only presents the characteristics of the innovations, not the innovations themselves,
 460 and space K in Fig 6 only presents the knowledge that was used to build the innovations, not the
 461 innovations themselves (see section 2.3.2). The innovations are listed in Table 2. The innovations cited
 462 here by the actors are innovative because they are not found on the territory of Martinique, or more
 463 particularly, in the Galion watershed territory, because our actors' innovations were designed with the
 464 main objective of reducing the use of herbicides, and because they are considered at the watershed
 465 scale independently of the agricultural sector to which they belong.

466 Table 2 lists the 15 innovations created during those workshops.

Line	Innovation	Description of innovation	By pooling	By promoting
1	Community of practice	Creation of a discussion group between farmers, all agricultural sectors included	knowledge	
2	Catalogue of judicious associations with "weeds"	Creation of a catalogue to identify and select local plants adapted to each type of crop for use as a competitive cover crop for weed control	knowledge	
3	Brush cutting service provider	Creation of a partnership between farmers who are located geographically close to each other in the watershed and a brush cutting company	services	
4	Market for « weeds »	Creation of a market of weeds for human consumption (medicinal plants, vegetables) or for use as animal fodder	resources	
5	Collective composting	Creation of an association of farmers for the management of one or more composters, for "weeds" produced by farmers and municipalities	resources	
6	Mutualization of the services of an itinerant livestock breeder	Creation of an association of farmers or a partnership that employs a livestock breeder with his herd to graze weeds growing on farms located geographically close together in the watershed	services	
7	Koudmen	Creation of a mutual aid group between farmers from different sectors in the watershed for weed control on each other's farms	Work force	
8	Co-exploitation of plots	Creation of partnerships between farmers from different agricultural sectors for the development and maintenance of fallow land or of land between main crops	resources	
9	Galion store	Creation of a local distribution network for products produced by the farmers in the watershed, in a store and/or under contract with consumers		Agricultural practices Territory
10	Diversification to orchards under contract	Creation of a partnership contract between farmers in the watershed and the processing plant in the watershed, to increase financial resources for better agricultural practices		territory
11	Showcase Watershed	Agreement between farmers in the watershed to formalize and adhere to a charter of good practices		Agricultural practices Territory
12	Grant for landscape conservation	Creation of a grant to conserve landscapes in the Galion watershed, (definition and collective description of these landscapes by the stakeholders of the watershed)		territory
13	Tourism	Creation of a network of tourist farms in different agricultural sectors associated with other tourist activities in the territory		territory
14	Training modules according to the context	Creation of training based not on crops but on the different soil and climate contexts, and possible innovations with no herbicide use	knowledge	
15	Consumer training centre	Creation of a training centre for consumers, focused on agriculture and issues of pesticides residues in water in products and alternatives	knowledge	

467

468 The breakthrough path was pursued in more depth: (i) based on the characteristics of the watershed;

469 (ii) in comparison with examples of innovations underway elsewhere; and (iii) in comparison with

470 existing examples in the territory in certain sectors or on some innovative farms. Without detailing all
471 15 innovations, here we present their guiding principles.

472 Regarding pooling (Fig. 6, a), the actors had several ideas concerning pooling the work force, for
473 instance, by creating a work group composed of farmers living in the territory to help with hand
474 weeding, pooling the services of a low-cost brush-cutting provider or of an itinerant cattle breeder to
475 graze weeds on neighbouring farms. By extending the functions of weeds, the actors also thought
476 about pooling grass resources for sale (for medicinal purposes, as vegetables, as animal fodder), or
477 using weed resources and composters to make shared compost or to feed animals on neighbouring
478 farms. The two last innovations are only compatible with hand weeding. Because the farmers
479 appreciated exchanging knowledge with other farmers, and because weed control is an integral part of
480 all cropping systems, they also wanted to continue pooling their knowledge despite belonging to
481 different agricultural sectors. This innovation could help them better understand the dynamics of the
482 territory's weeds, and to find and share solutions for weed control without the use of herbicides.

483 Regarding promotion (Fig. 6, b), the actors wanted to promote the Galion watershed based on its
484 agricultural identity, first through sustainable practices such as reduced herbicide use, then by
485 developing a label for their crops (either specific to the basin, or part of an already existing quality
486 label), or by creating short supply circuits specific to the watershed. Another idea for promoting the
487 watershed was based on the creation of an ecotourism circuit label based on the rich agricultural
488 diversity of the watershed, which is representative of agriculture in Martinique. This label would
489 provide financial resources that could then be used to reduce herbicide use. The innovations were not
490 only designed during the workshops, for instance, the idea of selling certified products from the
491 watershed was put forward on the ecotourist circuit.

492 Group discussions also made it possible to identify the criteria (see 2.3.3) the stakeholders preferred to
493 evaluate a watershed with low concentrations of agricultural herbicides in the river that was the object
494 of the design, namely: (i) reduced herbicide use; (ii) increased financial resources for farms
495 (mentioned by non-farming stakeholders); (iii) reduced work time for farmers (mentioned by the
496 farmers); (iv) promotion of the watershed as a place of good agricultural practices; and (v) more
497 pooling of resources between farmers to create solidarity.

498 To sum up, at this point we had successfully explored the breakthrough path, but the best way to
499 implement the innovations to reduce the presence of herbicides in the river remained to be found. This
500 was this knowledge gap we wanted to fill with design in use, using the serious game.

501 3.3. Game to simulate the design of innovations in use

502 The research team selected six innovations out of the 15 (Ecotourism; a charter “Watershed with good
503 agricultural practices”; Farm diversification to arboriculture; Itinerant livestock breeder; Brush cutting

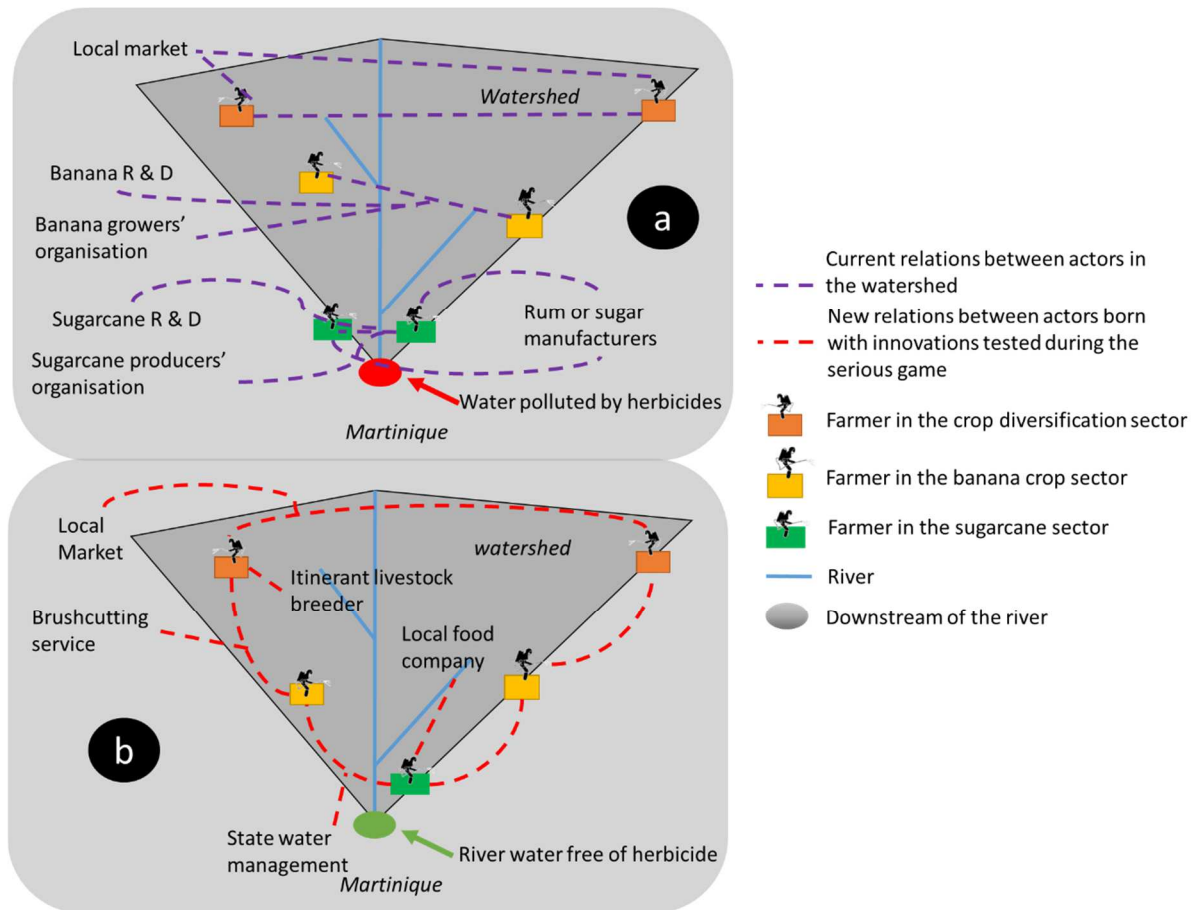
504 service provider; Mutual aid group between farmers) to cover the entire C tree of the diagram C-K in
 505 Fig. 6, i.e. by selecting an innovation by each concept of partition 6, and to cover all the evaluation
 506 criteria. These innovations were implemented in the game.

507 During the game, players chose which innovations they wanted to apply. Groups of players were
 508 formed based on a shared choice to stick to certain collective innovations. This enabled us to
 509 distinguish three scenarios, which we evaluated with respect to herbicide pollution in the river and
 510 additional criteria (Table 3). All three scenarios led to a in reduction in herbicide pollution of the river.

511 Table 3: Innovation tested in the three scenarios run during the serious game workshop

	Scenario 1	Scenario 2	Scenario 3
Innovations chosen by the players	Ecotourism Brush-cutting service provider Diversification to orchards under contract	Charter « Watershed with good agricultural practices » Brush-cutting service provider Itinerant livestock breeder	Charter « Watershed with good agricultural practices » Farmers' mutual aid group Itinerant livestock breeder Universal grants

512 Scenario 2 is the one that fulfilled the most criteria, especially in increasing the labour force available
 513 for agricultural tasks on 75% of the farms. Financial resources remained stable for 75% of the farms
 514 and were reduced for 25% of the farms. This led to a 76% reduction in herbicide pollution of the river.
 515 During the game, new relationships were formed between the actors. First, implementing the
 516 innovations brought together actors who in real life are not so close. Second, relationships were also
 517 formed between players, especially between the water manager and the farmers. Concerning the
 518 relationships linked to the implementation of innovations, the scenarios put farmers in the same sector
 519 in the watershed in touch with one another by getting them to participate in the same charter, or in the
 520 ecotourism circuit. Finally, these new farmers' networks were put in contact with other actors of the
 521 territory, in particular those involved in water quality monitoring, which enabled certain collective
 522 innovations to be implemented through subsidies, or in collaboration with service providers outside
 523 the watershed. As a result, by combining the combinations of successful innovations within the
 524 territory, that have been played in the three scenarios, we were able to design watershed-scale and
 525 transboundary solutions to achieve low concentrations of agricultural herbicides in the river (Fig. 7). It
 526 was the combination of the solutions within the watershed territory in the game that led to the
 527 successful design of a new configuration in this watershed, and to low concentrations of agricultural
 528 herbicides in its river. This new watershed represented the initial C0 concept we had wanted to design
 529 all along.



530

531 *Figure 7: Schematic diagram of the main relationships that existed in the watershed before the design*
 532 *process began [purple dashed lines in (a)] and at the end of the design process [red dashed lines in*
 533 *(b)]. The new relationships [red dashed lines in (b)] between the actors in the watershed were created*
 534 *during the serious game. Farmers from the three agricultural sectors became acquainted when the*
 535 *innovations were tested. Members of these new farmers' networks also met other actors already*
 536 *present in the watershed, as well as new actors outside the watershed. These new relationships help*
 537 *reduce the level of herbicides in the river [green oval].*

538 4. Discussion

539 4.1. Advantages and limits of the method

540 Our method enabled us to propose a new way to organise the watershed and to reduce herbicide
 541 pollution in the river, as well as the emergence of new networks between actors at the watershed scale
 542 and across agricultural sectors and different types of actors. We therefore recommend its use in other
 543 territories which require changes in collective practice, particularly, but not only to limit pesticide
 544 pollution. In this section we explain how this new method enabled this success, along with its
 545 limitations, and present a reformulation of the method for generic use.

546 Adapting theoretical and methodological frameworks to the territory

547 As recommended by Belmin et al. (2017) and Raven et al. (2012), in our socio-technical diagnosis it
548 was necessary to spatialize the concept so that it could be applied to the small territory represented by
549 the Galion watershed. Indeed, the framework of a sociotechnical system is appropriate to study the
550 normative and regulatory rules that apply to a territory, and to focus on institutional mechanisms
551 (Lamine et al., 2019). In our case, the watershed is not a defined space for agricultural management,
552 nor a space that is present in the representations of most of the actors, except for actors of water
553 management. We therefore had to study these rules at the scale of the whole island of Martinique, and
554 then to make assumptions about their impact within the spatial limits of the watershed. Other authors
555 who sought to link the socio-technical system to a territory encountered the same difficulties. By
556 carrying out a more local resizing, these studies established the boundaries of the system to be studied
557 through territorial or sector projects related to the existence of normative and regulatory rules (e.g.
558 PGI clementines in Corsica (Belmin et al., 2017); the organic agriculture sector (Lamine, 2012); or
559 institutional projects (Allais and Gobert, 2019)).

560 Choices made by the research team that guided the design process

561 In the creative exploration stage (stage C), we made choices concerning the fixation effects to be
562 overcome in the process that would increase the emergence of innovations on a territorial scale. That
563 is why we focused on two fixation effects, i.e. (i) innovating within their agricultural sector and (ii) at
564 the plot scale, that were common to all three agricultural sectors, and ignored the fixation effect related
565 to sugar cane and banana monocropping. Although the innovations designed also concern the banana
566 and sugarcane sectors, they do not directly call into question the successions of monocrops (banana,
567 sugarcane). This fixation effect, although clearly identified in the diagnosis, was not retained in the
568 following stages because it did not concern all the actors, in particular the diversified agricultural
569 sector. This phenomenon was also reported in Ravier et al. (2018), where the innovations developed
570 did not include the scale of the innovations, and in Vourc'h et al. (2018) who sought to develop
571 transdisciplinary projects, but where all the new projects still focused on technical changes on farms.
572 This phenomenon underlines the importance of the choice of fixation effects to be overcome, which
573 guides creative exploration. To overcome the fixation effect on monocropping, the KC workshops
574 should have focused on overcoming this particular fixation effect. As a result, certain paths were not
575 explored, even when they could have led to breakthrough innovations.

576 Building consensus

577 In C-K theory, changes in the participants' knowledge lead to changes in the definition of a concept,
578 and in turn, in the representation of the object. During the workshops, we observed changes in the
579 representations of the object to be designed – which made it possible to collect new evaluation criteria
580 from the actors – and a desire to create a specific agricultural identity for this watershed. This is
581 consistent with the findings of Bretagnolle et al. (2018) and Prost et al. (2003), who reported that

582 knowledge is more a construction than a discovery. Allowing the ongoing review of the fundamental
583 properties of the object under design between the actors is a major advantage in innovative design
584 (Berthet et al., 2019). What is more, we went from design that considers the territory as a context, to
585 considering the territory as a design object, which is part of the changes in the relationship between
586 design and territory as understood by Parente and Sedini, (2017). The actors changed their
587 representation of the watershed, which they had initially not perceived as a management scale. In fact,
588 participatory design processes like ours, focused on the development of a new social and ecological
589 system, reinforce the actors' sense of ownership and responsibility (Berthet et al., 2019).

590 Actors' motivation

591 During our study, we succeed in achieving the necessary representativeness of the actors, but we had
592 problems keeping the same actors involved throughout the process and witnessed a decline in
593 participation over time.

594 We chose to set up a collaborative participation process steered by the researchers, with the active
595 collaboration of the participants and sharing of knowledge about the watershed. However, the
596 development of the design method was not discussed with the actors, and we partially failed to clearly
597 explain our objectives regarding the methodological development of the design process. According to
598 Kellon and Arvai (2011) this is something that is regularly criticized in participatory processes. But
599 sharing our design objectives with the actors is difficult in a method where the object to be designed is
600 not defined right at the start but is constructed progressively. Barreteau et al. (2006) argue that when
601 participants do not really know what to expect in a participatory process, or even when certain power
602 relationships between actors are at stake (Barnaud et al 2010), there may be disappointment, which
603 may jeopardize their participation. To overcome this problem, Pahl-Wostl et al. (2007) point to the
604 need to develop a sense of legitimacy in decision-making among all participants, as this encourages
605 them to participate in the process. Kellon and Arvai (2011) and Mintrom and Luetjens (2016) argue
606 that this requires that the collective of actors do not feel they are being used by the researchers, i.e.
607 perceive their participation as a mere formality, but feel they really participate in decision-making. To
608 avoid this problem, it should be made clear to the participants at the start that the object to be built has
609 not yet been defined, and that the aim of our participatory method is to develop the collective
610 creativity of the participants, and in this way to incorporate their decisions into the design of the
611 object.

612 The power of the KC method to motivate participants can be examined in terms of the originality and
613 novelty of the solutions designed with the method. In some workshops, participants said that they
614 disliked using projector concepts (see section 2.3.3) that were too far removed from their own
615 representations. Others questioned the feasibility of very original solutions. It is thus necessary to
616 examine the difficulties peculiar to the KC method, i.e. maintaining the involvement of a group of

617 actors throughout the design process, and how this difficulty can be overcome. As innovative design
618 was originally developed in companies (Hatchuel, 2018) where participants are generally encouraged
619 to work together and who share the same corporate objectives, the capacity of the method to motivate
620 actors has not been challenged to date. However, the difficulty in getting actors involved in processes
621 outside companies has been reported in other studies (e.g. Pluchinotta et al., 2019). In these studies,
622 the facilitators used different strategies to keep the actors motivated throughout the process, for
623 instance, by linking stages K and C on the same day (Berthet, 2013; Ravier et al., 2018), or using
624 semi-structured interviews with the actors in stage K rather than collective workshops (Pluchinotta et
625 al., 2019).

626 About the future of this participatory process

627 This participatory process responds to the changing relationship between design and territories, by
628 designing for territories. This approach automatically involves stakeholder participation and the
629 creation of intermediate artifacts (such as the game or the standard C-K diagram) to compensate for
630 the excessive complexity of the system to be co-designed (Parente and Sadini, 2017). As the territory
631 is a non-static, constantly changing context, design tools and devices must be flexible (Parente and
632 Sadini, 2017), which in turn, implies that this type of device should take the form of evolving and
633 perennial institutions. With financial support, this participatory process could become permanent by
634 becoming an entity inspired by the socio-ecological research platforms presented in Berthet et al.
635 (2019) and Bretagnolle et al. (2018). Those platforms will enable the capitalization of knowledge on
636 the dynamics of the socio-ecological system, while developing collaboration and synergies between
637 design facilitators, ecologists, and local actors Berthet et al. (2019). These platforms are not limited by
638 traditional disciplinary boundaries, since they operate at a spatial scale that is large enough to involve
639 all actors, and use systems approaches to study the links between ecological and social systems
640 (Bretagnolle et al., 2018). These platforms can coordinate the actions of stakeholders by taking the
641 knowledge of all the niches of the sociotechnical system into account, thereby safeguarding the niches
642 through their co-evolution due to the fact that the stakeholders no longer compete with each other (Le
643 Masson et al., 2012). That was the case here, where all the stakeholders of the agricultural sectors that
644 innovate in weed management were brought together to design scenarios combining and hybridizing
645 different technical innovations. But our work remains theoretical, and it would be necessary to
646 continue the development of the C0 by implementing some combinations of innovations in the
647 watershed.

648 To this end, a strategic vision of the future development of the territory needs to be designed using
649 these platforms, i.e. a preliminary framework of values and means between the actors, in order to help
650 the actors identify what they consider the best way to act (Parente and Sadini, 2017). As Mathevet et

651 al. (2016) argue, with the aim of preserving natural resources, these strategic visions can take the form
652 of ecological solidarity with a symbolic agreement between actors, on a territorial project.

653 4.2. Towards a generic method

654 The structure of our method (Table. 1), which combines four steps to design new ways of organising
655 territorial food systems, was successfully tested in this study. Here we complete it with four possible
656 improvements.

657 During the diagnosis (step 1) or at the beginning of the process design (step 2), our experience shows
658 that the initial questions that can arise - particularly in a group of actors - need to be discussed with all
659 the actors to achieve satisfactory reformulation and clarification of their expectations of the
660 participatory process. This will allow the actors to assess the time they can allocate to the process, but
661 also allow the facilitator to adapt his or her participatory process to the possible need to motivate the
662 group.

663 We recognise the efficiency of using the KC method in overcoming the fixation effects of actors
664 during Step 3 (the creative step). The K stage should open the actors' minds to breakthrough ideas by
665 sharing current knowledge, lack of knowledge, and original examples. Facilitators need to be aware of
666 all original knowledge or examples that could feed this dynamic process. In the C stage, the facilitators
667 need to be aware that projected concepts may disturb the participants, and that the actors will have a
668 strong reflex to return to their fixation effects. This is why facilitators need to be trained in innovative
669 design and be ready to give examples from other innovative design case studies to reassure the
670 stakeholders about the advantages and seriousness of these destabilizing conceptual detours, and of
671 their potential for generating new ideas. We had difficulty with one C workshop based on the concept
672 of the " Galion Watershed Grassland Management University", especially with the word "university"
673 which was a problem for the participants, as it seemed absurd and out of place. We were unable to
674 reassure the participants, and this workshop was in fact the least productive of the three C workshops.
675 At the end of this stage, the facilitators should be able to add evaluation criteria to the object designed,
676 based on the actors' own new ideas.

677 We also recognise the effectiveness of using a serious game, with or without a computer simulation
678 model (step 4) to develop the properties of situated innovations (even simulated ones) to continue to
679 design innovations. We suggest that the conceptual representation of the system concerned, as a basis
680 for the game, should be built collectively, according to the ARDI method (Actors-Resources-
681 Dynamics-Interactions) (Etienne et al., 2011). We suggest adding a step to the ARDI method: to
682 discuss with the actors how to choose and incorporate the innovations identified in stage C in the
683 game. The results of the game can then be evaluated against evaluation criteria, both the quality of the
684 resource at the basis of the design process, and on the evaluation criteria of the actors involved in the
685 KC stage.

686 Finally, we suggest the design process itself should be evaluated in two parts: an evaluation of the
687 design process by the participants during the process to enable improvement of the method all along
688 the way; and an evaluation of the capacity of the method to overcome fixation effects, by noting
689 changes in the participants' representation of the design object. Giving participants the time and
690 opportunity to evaluate the method during the process would likely reinforce their involvement and,
691 more importantly, the feeling that their opinions are taken into account in the process, which could
692 help ensure their continuing involvement.

693 5. Conclusion

694 We succeeded in creating territorial innovations to reduce the presence of herbicides in a river using a
695 new participatory design method that links socio-technical diagnosis, C-K theory, and serious games.
696 This method increased the relevance of innovations for four main reasons. First, the innovations went
697 beyond the scale of the plot to focus on a territory. Second, they were designed as a coherent system
698 since they were created and thought out simultaneously. Third, they overcame the cognitive biases of
699 agricultural actors who tend to innovate only within their own agricultural sector and at the plot scale.
700 Fourth, serious games made it possible to test these breakthrough innovations in a safe place. This
701 success proves that our new territorial innovation method can help develop efficient strategies to
702 reduce the pollution of a river. We thus recommend the method for use in situations where territorial
703 innovations are needed.

704 We recommend that innovations reorganise activities at the watershed scale: plot or farm level
705 innovation needs to be coordinated with, for instance, quality labels, shared agricultural tasks,
706 rotational grazing, or regulation of the watershed.

707 To ensure the success of the new method, we recommend an additional step to reinforce the
708 participatory mechanism with the stakeholders to guarantee their continued participation throughout
709 the key stages of the process. We also recommend adding a participatory step on how to include the
710 breakthrough innovations in the serious game.

711 Innovations were not the only result of our application of this new method: the method is also the
712 participatory system that combines the design of the territory and the water quality monitoring system.
713 This type of design mechanism could become permanent, for example, in the form of social-ecological
714 research platforms, to capitalize on knowledge on the dynamics of the socio-ecological system while
715 developing collaboration and synergies between the actors concerned.

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