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1 **How farmers learn to change their weed management practices:** 2 **Simple changes lead to system redesign in the French West Indies**

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12

13 **Abstract**

14 Herbicides used in agriculture pollute water worldwide. However, several weed management
15 alternatives can reduce herbicide applications. The understanding of interactions between agronomics
16 and the learning and social processes that favor changes in practices on a territorial scale is still far from
17 complete. Despite the call for systemic change approaches, most studies are still based on technology
18 transfer. Research and extension services provide references on alternative weed management practices
19 and promote their use among farmers. We surveyed 33 farmers in a 45 km² tropical catchment plus five
20 institutional extension services. We analyzed changes in weed management practices on the 33 farms
21 belonging to three different agricultural chains: local diversified horticulture, sugarcane, and export
22 banana. For each change, we analyzed the learning processes and the networks involved in information
23 exchanges. First, we show that the complexity of the practices promoted by extension services limits
24 their adoption. Second, we show that simple practices adopted by farmers are part of a slow trajectory
25 of change involving the gradual acquisition of knowledge. A redesign of cropping systems can emerge
26 as the result of a gradual adding of complexity in practices and/or a specific systemic change on a
27 cropping system scale. Sharing knowledge and resources in a non-competitive way speeds up changes

28 among farmers sharing resources and promotes the redesigning of cropping systems. Third, we show
29 that the structure and functioning of relational networks limit changes in practices on a watershed scale.
30 We thus recommend that innovation design should incorporate co-designing of the pathway of change,
31 by designing a succession of simple changes rather than a complex final system only. We recommend
32 including non-competitive resource pooling among farmers in the co-designing of innovation.

33 **Keywords:** herbicides; watershed; innovation; trajectory of change; learning process; farming networks

34 **Declarations of interest:** none

1. Introduction

35 Pests and weeds have negative impacts on crop productivity and quality worldwide. Farmers use various
36 techniques to protect their crops and stabilize their yields, one of the most problematic for the
37 environment being the use of pesticides. Thus, shifting to pesticide-free agricultural practices remains a
38 challenge. To that end, agronomists have sought ways of accelerating and facilitating cropping practice
39 changes among farmers. Considerable research efforts have been made by researchers, farmers, and
40 extension workers to find new crop protection strategies and techniques, and to understand their
41 interactions (for a review see Schut et al. (2014)). Schut et al. (2014) found that the majority of these
42 efforts focused on transferring a technology from research or from an extension service to farmers, while
43 more systemic approaches (agricultural knowledge and information systems, agricultural innovation
44 systems) are required to enhance the resilience of crop protection systems. Accordingly, Wigboldus et
45 al. (2016) explained that the dominant methods for scaling innovations are empirical and based on the
46 premise “find out what works in one place and do more of the same in another place”. This approach
47 simplifies the complex processes of practice changes. On the one hand, the technology transfer approach
48 highlighted the effects of the technical characteristics of innovation, the characteristics of the farm, the
49 farmers themselves, and other exogenous, unmanageable factors (e.g. socio-economic and pedo-climatic
50 contexts) in the adoption of innovations (Blazy et al., 2009a; Blazy et al., 2009b; Roussy et al., 2014;
51 Schut et al., 2014). On the other hand, Kilelu et al. (2014) showed that because learning in agricultural
52 innovation processes is dynamic, static notions of demand articulation and related support are
53 inadequate. The more recent knowledge and information systems approach has broadened knowledge
54 on the factors that influence practice changes. Sutherland et al. (2012) conceptualized changes on a farm
55 scale in a dynamic way. They showed that major changes on a farm follow a pattern of “trigger events”
56 while minor changes are made incrementally, with both following a path dependency. Lamine (2011)
57 and Chantre and Cardona (2014) showed that changes in cropping systems rely on an individual learning
58 process within a farmer’s sociotechnical trajectory. Klerkx et al. (2012) showed that innovation in
59 agricultural systems goes beyond seeing research as the main input to change and innovation, and
60 recognises that innovation emerges from complex interactions between multiple actors. Learning
61 processes involve personal and external information originating from the farmer’s experience and social
62

63 interactions (Chantre, 2011; Chantre et al., 2015; Ingram, 2008; Schneider et al., 2009). Compagnone
64 and Hellec (2015), Lowitt et al. (2015) and Saint Ville et al. (2016) highlighted the importance of social
65 interactions in the territorial dynamics of change in different contexts and showed that collective sharing
66 of local specific knowledge fosters the design and spread of innovative practices. Therefore, knowledge
67 exchange between different stakeholders appears to be a key triggering event for practice changes. But
68 what kind of changes? Qualifying changes has always been a tricky issue, especially as changes might
69 be seen as subjective. Nevertheless, classifying modified systems according to conventional system
70 references was proposed by Hill and MacRae (1996) and Altieri and Rosset (1996) in order to assess
71 sustainability. They showed that changes could be of an efficiency, substitutive, or redesign nature.
72 According to Sutherland et al. (2012), two types of changes exist, minor and major, while for Aubry and
73 Michel-Dounias (2006) changes might be classified according to the decision level they involve: tactical,
74 operational, or strategic.

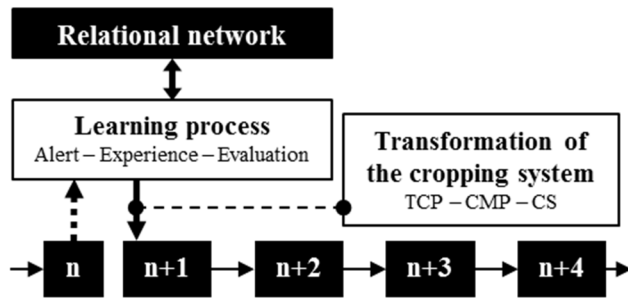
75 Due to the requirement of sustainable agricultural practices, we have seen an increasing amount of
76 research highlighting the importance of learning and social interactions in the evolution of cropping
77 systems (Chantre and Cardona, 2014; Houdart et al., 2011; Ingram, 2010; Toderi et al., 2007). Along
78 with the classification of changes, the expectation is to understand whether generic knowledge on how
79 the different types of change are triggered can be identified (Sutherland et al., 2012). The present
80 document argues in favor of the role of learning in the redesigning of cropping systems within farmers'
81 sociotechnical trajectories. Our hypothesis is that a change in weed management practices on a farm
82 scale is intrinsically linked to the learning process that anchors it in the farmer's sociotechnical
83 trajectory. It implies that individual processes interact with collective processes in designing and
84 exchanging new practices in a territory (including the physical and social dimensions). In order to
85 formalize the process of change on a generic basis, we built a generic analysis framework that makes it
86 possible to (Figure 1 and §2.1): **(i)** qualify the technical changes in cropping systems, **(ii)** describe the
87 learning process farmers require to implement the changes and, **(iii)** report the affiliations they make
88 with "others" on crop management issues to enable the process of change.

89 We conducted the study in the French West Indies, where large amounts of pesticides have been used
90 in the past. This has resulted in generalized pollution by chlordecone on an island scale (Cattan et al.,
91 2019). That pesticide still contaminates soils, fresh water, several crops grown on polluted soils and
92 livestock (Clostre et al., 2017; Crabit et al., 2016; Della Rossa et al., 2017; Mottes et al., 2019). Human
93 exposure has adverse effects on health (Multigner et al., 2016). Although chlordecone environmental
94 pollution still exists, such pollution has raised the level of awareness among inhabitants and farmers in
95 the French West Indies (FWI) about the dangers of pesticides, generating strong social demand to avoid
96 pesticide use in cropping systems. Nowadays, the most used pesticides in the FWI are herbicides,
97 because all crops are affected by weed competition. In spite of farmers' willingness to avoid herbicides,
98 they are still largely applied all year round in tropical cropping systems because of climatic conditions
99 conducive to weed development. The combined use of herbicides on the different fields on a watershed
100 scale generates pressure that spreads over time and inevitably results in water pollution (Mottes et al.,
101 2017). As a result, a major challenge to solving the pollution problems is switching to cropping systems
102 that use less herbicide. Using surveys of farmers and supervisors of agricultural and environmental
103 organizations, we applied the framework to a watershed with significant herbicide pollution issues in
104 the FWI. We investigated the diversity of changes, processes and networks brought into play by all types
105 of farmers located in a 45 km² watershed in order to identify the different pathways for change. We
106 expected this integrated approach to produce recommendations on how research and extension services
107 could help to support more ecological farming practices within the territory.

108 **2. Materials and methods**

109 **2.1. Theoretical framework**

110 In order to formalize the process of change on a generic basis, integrating the different dimensions of
111 changes, we built our own framework that relied on a combination of existing frameworks. Based on
112 our hypothesis, we built a framework (Figure 1) that made it possible to analyze conjointly: **(i)** the nature
113 and complexity of the technical changes in the cropping systems (§2.1.1), **(ii)** the learning process
114 farmers required to implement the changes (§2.1.2) and, **(iii)** report on the affiliations they make with
115 “others” on crop management issues to enable the process of change (§2.1.3).



116

117 Figure 1: The theoretical analysis framework elaborated (n = successive states of the cropping system; dotted
 118 arrow = exploration of new solutions through a learning process; double-headed arrow = interaction with the
 119 dialogue network within the learning process; solid arrow = implementation of a change in the cropping system).

120 **2.1.1. Qualifying cropping system changes within farmers' trajectories**

121 Our framework conceptualized farmers' trajectories as a succession of stable phases during which
 122 management practices remained unchanged, and technical changes that took place between the stable
 123 phases (Figure 1). Each technical change in the cropping system could have been related to a
 124 classification in existing frameworks (Hill and MacRae, 1996; Sutherland et al., 2012). Nevertheless,
 125 such classifications might seem rather conceptual for farmers. This is why, in our framework, each
 126 technical change in cropping systems could be described by related transformations at three different
 127 levels of cropping system management (Doré and Meynard, 2006; Sebillotte, 1990; Shrestha and
 128 Clements, 2003) - Figure 1: (i) The modification of a technical characteristic of a practice. The change
 129 is simple because the farmer modifies only one technical aspect of a practice (e.g. dose applied, tillage
 130 depth, mowing height, molecule used, tool used). (ii) The modification of a crop management practice
 131 (e.g. replacement of chemical weeding by manual or mechanical weeding). The change is slightly more
 132 complex because the farmer modifies the crop management practice and all its associated technical
 133 parameters. (iii) The modification of the cropping system. This includes modifications to the nature of
 134 crops or their organization over space and time (e.g. diversifying crops, replacing a crop by another,
 135 enlarging the inter-row of perennial crops, intercropping, modifying a planting date). This also includes
 136 the organization of management practices over space and time (e.g. integrating a new practice in crop
 137 management, modifying a treatment/operation date, implementing a change in a practice that
 138 automatically entails other changes in other practices). These changes are complex because the farmer

139 modifies several crop management practices, their technical characteristics and their organization over
140 space and time in a systemic way. Such changes could be seen as loosely coupled systems according to
141 Coughenour (2003), because the system is modified in its different components while aiming to achieve
142 several goals. On the other hand, technical and practical modifications are closer to tightly coupled
143 systems where most components of the systems remain unmodified by the change.

144 **2.1.2. Individual learning processes**

145 We broke down each change that occurred in the farmers' trajectories with a learning process approach
146 (Figure 1). To this end, we used the three steps identified by Chantre (2011) in the Lewinian experiential
147 learning model (Kolb, 1984). The three steps describe each change in a farmer's sociotechnical
148 trajectory: **(i) The Alert Step** goes from the identification of a problem, to the emergence of an idea and
149 the awareness of a potentially new practice. **(ii) The Experiential Step** consists in experiencing the idea
150 from the alert step. It allows the farmer to endorse the new practice. **(iii) The Evaluation Step**, the
151 farmer compares the results from the experiential step with personal or external references, leading
152 him/her to incorporate the change in his/her cropping system.

153 **2.1.3. Collective learning processes**

154 During each step of the learning process, a farmer gathers information from both his/her personal
155 experience and external sources (Chantre et al., 2014; Kilpatrick and Johns, 2003; Roussy et al., 2014).
156 According to Lazega (1994), Compagnone and Hellec (2015) and Saint Ville et al. (2016), the nature of
157 the relations between stakeholders influences both collective and individual change. Accordingly, our
158 framework integrated the way farmers exploit external references from their professional networks in
159 their personal learning process (Figure 1). This allowed us to re-create the structure of the relational
160 networks between farmers and extension services that influence weed management practices, in order
161 to understand the collective learning processes involved.

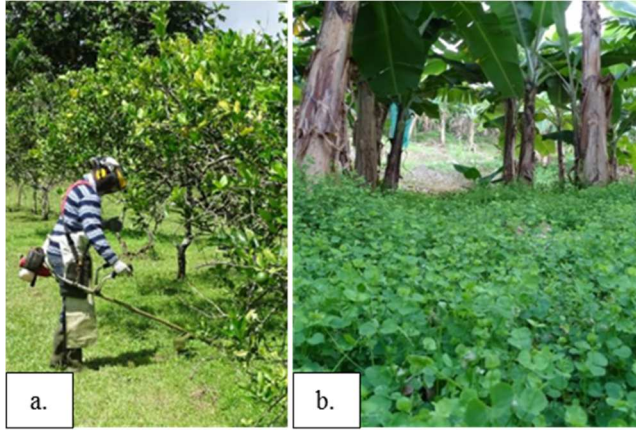
162 **2.2. Study site**

163 The study was conducted in the 44.5 km² Galion River watershed, Martinique, French West Indies
164 (61°4.4004'W/14°36.5352' N), whose elevation ranges from 0 to 694 m asl. The watershed is divided

165 into three agroecological zones (Della Rossa et al., 2017; Mottes et al., 2019)): (i) An upstream
166 mountainous zone with steep slopes (> 80%), abundant annual rainfall (3,500 to 4,000 mm.y⁻¹), with
167 mainly small mixed farms, livestock and traditional crops, with a utilized agricultural area (UAA) of
168 less than 4 ha,. (ii) A hilly zone with a more gently sloping topography (35%), annual rainfall of about
169 2,500 mm.y⁻¹, characterized by banana (*Musa* spp.) farms: UAA from 4 to 150 ha and small mixed
170 farms. (iii) A downstream floodplain with a relatively flat topography (slopes < 35%) and low annual
171 rainfall (1,500 mm.y⁻¹), characterized by small sugarcane (*Saccharum officinarum*) farms (UAA < 15
172 ha), one large industrial sugarcane farm and some large banana farms (UAA > 50 ha).

173 In 2015 (2015 Agricultural Census), the total cultivated area comprised 1,090 ha (1/4 of the watershed).
174 As the land area is unequally distributed in Martinique, export crops (banana and sugarcane) occupy
175 82% of the cropped area (560 and 330 ha, respectively). The two crops were grown on 1/3 of the 157
176 identified farms (17 banana farms and about 30 sugarcane farms). Even among these farms, land
177 distribution was unequal (e.g., one sugarcane farm occupied 200 ha out of a total of 330 ha of
178 sugarcane). About a hundred small farms (< 10 ha) with varying degrees of diversification shared the
179 remaining cropped area and sold their products on the local market.

180 The Galion watershed is polluted in a chronic manner by herbicides and herbicide metabolites
181 originating from the different cropping systems in the watershed. For instance, in 2016 we took weekly
182 water samples in the Galion river and metolachore was found in 50% of the samples, glyphosate in more
183 than 20% of the samples and AminoMethylPhosphonic acid (AMPA) in more than 90% of the samples
184 (Deffontaines and Mottes, 2017). Several farmers in the watershed use alternative weed management
185 practices, as illustrated by Figure 2.



186

187 Figure 2: Examples of alternative weed management practices in the Galion River watershed (a. brush-cutting in
188 a citrus orchard; b. cover-cropping in banana).

189 **2.3. Implementation of the survey**

190 The same person conducted semi-structured interviews with all 33 farmers and five supervisors from
191 the agricultural and environmental organizations mentioned by the farmers as having an influence on
192 their trajectory. We surveyed farms with the three main agricultural sectors: export bananas, sugarcane
193 and local diversified horticulture according to the 6 farm types identified by Raimbault (2014) in the
194 watershed (export banana, large sugarcane farm, small sugarcane farm, plantain banana, floral
195 horticulture and other fruit, tuber and vegetable farmers). Our objective was to survey at least 10 farmers
196 in each main sector to obtain a balanced sample between agricultural sectors. Only one floral
197 horticulturist and one large sugarcane farm were present in the watershed, and were selected to be
198 surveyed to represent their farm type in their agricultural sector. The other farmers were selected
199 randomly from the list established by Raimbault (2014). If the farmer was unreachable, we contacted
200 another until we managed to survey 10 farmers per farming system, which we did not manage for
201 sugarcane farms. When it was possible, we also surveyed farmers whom we had already identified as
202 having an influence on the evolution of their weed management practices (we added farmers B06, B07,
203 C07, C09 and D05). We did this to identify key farmers involved in processes of change on a territorial
204 scale. However, we limited the surveyed farmers to those located in the watershed. Lastly, we
205 interviewed 12 banana farmers (eight large-scale and three small-scale farms; noted **B**), nine sugarcane
206 farmers (one large-scale and eight small-scale farms; noted **C**) and 12 farmers with diversified farming

207 systems (one large-scale flower farm, one large-scale plantain farm, one small plantain farm, one small
208 citrus farm, and eight small tuber and horticulture farms; noted **D**). The characteristics of the farmers
209 are summarized in Supplementary Table SI.A. We asked questions about weed management practices
210 over the five years preceding the survey. The interviews were used to describe the farmer's
211 sociotechnical trajectory. Each change **(i)** was qualified according to the framework illustrated in section
212 2.1.1; **(ii)** according to the framework described in section 2.1.2; the elements from the alert, experience
213 and evaluation steps of the learning process of each change were discussed and summed up with each
214 farmer; and **(iii)** in the meantime, for each step in the Kolb cycle, relations with the network were
215 surveyed and classified according to information sources, representatives and type of interaction for the
216 three steps of the learning process (section 2.1.3).

217 During the surveys of the institutional extension service representatives, we identified: **(i)** the weed
218 management practices and changes in cropping systems they promoted; **(ii)** the terms of the support
219 system and its potential effectiveness (Who receives the messages and how?); **(iii)** the relationship
220 between the extension service and other institutions.

221 Lastly, we combined all the results in Table 1, classifying the changes identified in farmers' trajectories
222 and/or promoted by institutional extension services according to: (i) their information transfer pathway
223 (institutional extension services or farmer-to-farmer exchanges), (ii) the required modifications in the
224 cropping system (framework in section 2.1.1) and (iii) their adoption rate in the farmer groups concerned
225 by the transfer (adoption rate = number of farmer applying practice / number of farmer in the group). In
226 order to illustrate our reasoning, we selected six trajectories presented in Figure 3. We chose them
227 because they led to a unique way of managing weeds in the corresponding production system and/or
228 presented a modification of the cropping system in a systemic way at some point. By combining
229 collected information on the relations between farmers and their sources of influence (other farmers,
230 extension services, selling organizations, research, etc.), we re-created the structure of the relational
231 networks in Figure 4.

232 **3. Results and discussion**

233 **3.1. The less complex a change, the greater the adoption by farmers**

234 Table 1 lists alternatives to standard weed control using herbicides that we identified in the watershed
235 for banana, sugarcane and local diversified horticulture farming systems. The main technical changes
236 (Table 1 - column 3) in the three farming systems were mechanical weeding (using different equipment),
237 and soil cover (mulching or cover crops). Except for local diversified horticulture, diversifying crop
238 sequences or introducing intercropping to reduce weed pressure was neither adopted, nor proposed as
239 an alternative.

240

	Transfer pathway Strategy	Description of the change	Required modification in			Adoption rate (Number of farmers)
			Technical charact. of the practices (TCP)	Crop management practices (CMP)	Cropping system (CS)	
Export banana 12 farmers	Extension services (and farmers for CMP) Inter-row cover cropping	Maintaining an implemented single or multi-species cover that may include legumes	Do not destroy useful weeds	From chemical to mechanical weeding	Sowing/ planting the cover.	TCP : 58% (7) CMP: 67% (8) CS: 0%
	Farmers Mechanical weeding	Optimizing mechanical weeding with large machinery	Replacing brush-cutter ¹ by rotary-slasher ²		Replanting with larger inter-rows	17% (2)
Sugar cane 9 farmers	Extension services Avoid weed development	Combining pre- and post-emergence herbicides (respectively just after harvest and 2-3 months post-harvest)	Using a pre-emergence herbicide for the first treatment		Moving up the first herbicide treatment to just after harvest	TCP : 33% (3) CS : 0%
	Farmers Delay first herbicide until canopy closure	Hand weeding	Extending hand-weeding			89% (8)
		Mulching with cane residues	Distributing cane residues			33% (3)
		Replacing hand-weeding by brush-cutting ¹		From manual to mechanical weeding		33% (3)
Local div. Horticult. 12 farmers	Extension services Soil cover to limit weed development	Producing organic mulch for horticultural crops			Cultivating plants for straw. Installing the mulch	0%
		Plastic or paper soil cover			Installing the cover	0%
		Wide range of changes (hand/mechanical weeding, tillage or intercropping) with variable modifications in TCP, CMP and/or CS.				
	Farmers Improve traditional practices	E.g.1: intercropping yam growth period	Enlarging inter-rows when planting		Adding a crop compatible with yam	
	E.g.2: brush-cutting ² in a sensitive crop (taro)		From manual to mechanical weeding	Precise inter-row space and cutting-line length		
	E.g.3: weeding with large machinery in plantain	Replacing brush-cutter ¹ by rotary-slasher		Replanting with larger inter-rows		

(1) Brush-cutter: hand-held power tool used for trimming weeds and other foliage.

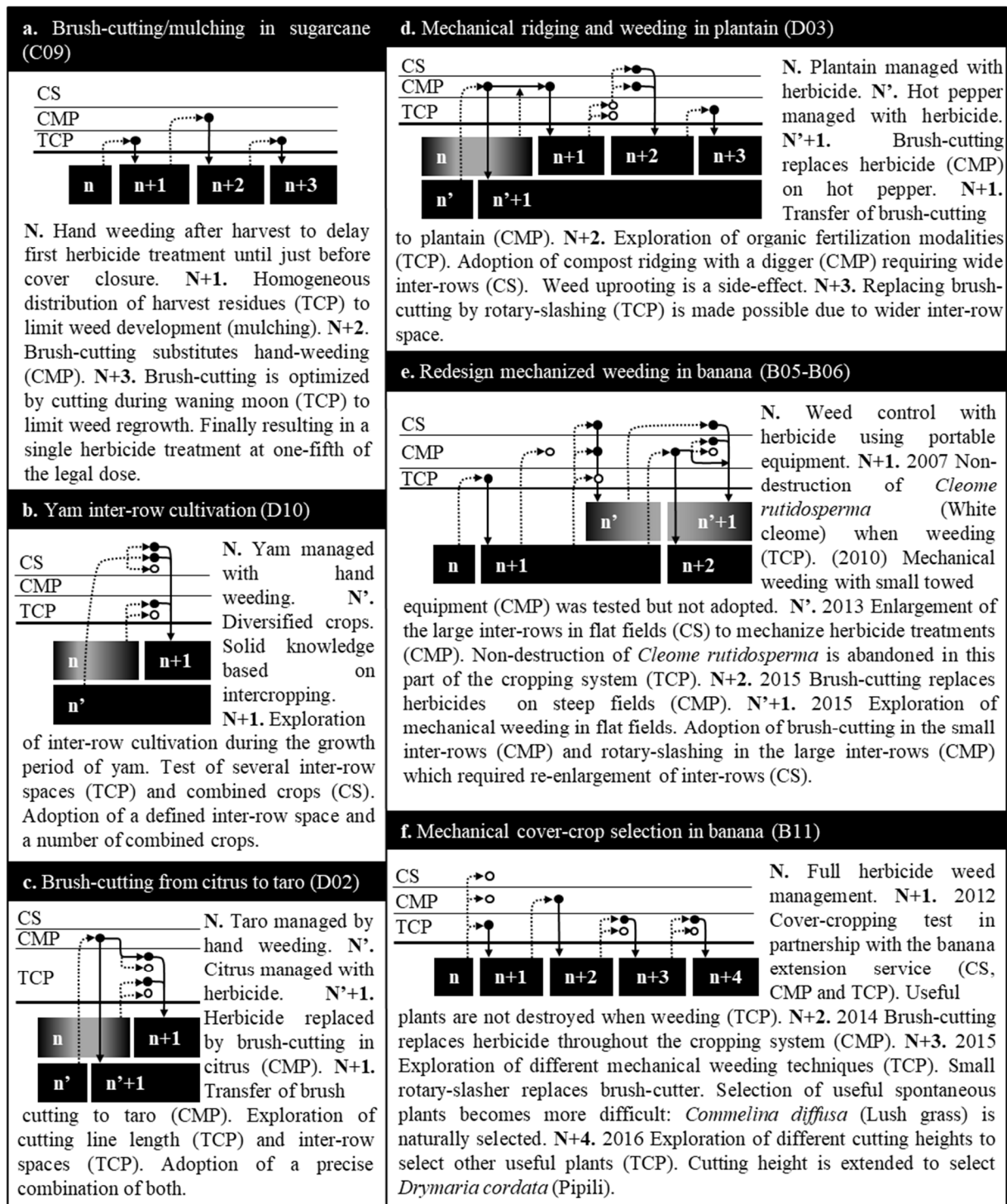
(2) Rotary-slasher: power machinery towed by a tractor that uses a rotating blade to cut vegetation.

241 Table 1: Description of changes according to: (i) their transfer pathway; (ii) required modification to the technical
242 characteristics of the practices (TCP), crop management practices (CMP) and cropping system (CS); (iii) their rate
243 of adoption.

244 Table 1 shows that most of the surveyed farmers modified the technical characteristics of practices
245 (TCP), or their crop management practices (CMP). Both were relatively simple changes (see section
246 2.1.1). Only two banana growers and three diversified farmers modified their entire cropping system
247 (CS). Table 1 also shows that the complete adoption of recommendations made by extension services
248 would have required complex systemic modification of the cropping systems (Table 1, section 2.1.1).
249 We did not observe any such modification, but 12 farmers did modify parts of their practices in line with
250 the main strategy of the recommendation. They applied the general agronomic concept of covering the
251 ground with living biomass, but they changed in a simpler way by modifying only crop management
252 practices (such as replacing chemical weeding by mechanical weeding with a brush-cutter), or the
253 technical characteristics of a practice (such as selecting spontaneous useful weeds by chemical spotting)
254 (Table 1). The farmers' behaviors that we observed supported the statement of Bal et al. (2002)
255 concerning innovation: the more complex an innovation, the more difficult its transfer and adoption by
256 farmers. According to (Roussy et al., 2014), the main reason for the rejection of an innovation is the
257 farmer's perception of the risk involved in the change, in other words the farmer's uncertainty about the
258 potential advantages of the change and how much it will cost. Hill and MacRae (1996) pointed out that
259 the more complex the change, the higher the financial uncertainty. They also agreed with Toffolini et
260 al. (2017) who stated that the expert knowledge required to understand complex and systemic changes
261 on a cropping system scale jeopardizes their adoption: complex changes require complex knowledge,
262 which corresponds to a resource required to implement the change. Simple changes require relatively
263 little knowledge or financial investment, which makes adoption of simple practices relatively easy. In
264 our case, complex changes promoted through classical extension service methods (top-down transfer)
265 were much more difficult for farmers to adopt.

266 **3.2. Joint construction of practices and knowledge in farmers' trajectories**

267 Figure 3 presents six examples of changes in farmers' weed management practices. We chose them
268 because they managed weeds in a unique way in their production system (farmers C09, D03 and B11),
269 or they modified their cropping system at some point (farmers D10, D02, D03 and B05-B06).



270

271 Figure 3: Examples of changes in weed control practices in farmers' trajectories. (N and N' = two distinct cropping
 272 systems on the same farm; dotted arrows = exploration; solid arrows = implementation in the cropping system;
 273 black dots = implemented changes; empty dots = abandoned changes; each change was classified according to
 274 required modification to the TCP = Technical characteristics of a practice, CMP = Crop management practices
 275 and CS = Cropping system).

276 **3.2.1. Successive and coherent changes in farmers' trajectories**

277 Figures 3a and 3f show that the changes undertaken by farmer C09 and farmer B11 in their trajectories
278 modified crop management practices, or their technical characteristics, but not the cropping system.
279 Thus, changes were relatively simple. All the farmers we surveyed, except D03, D10, D02, B05 and
280 B06, had trajectories made of simple successive changes only, such as the ones made by C09 and B11.
281 The existing cropping systems were hardly disrupted, supporting the suggestion by Bal et al. (2003) and
282 Meynard et al. (2012) that an innovation should only cause limited disturbance to be compatible with
283 an existing system. Moreover, changes are implemented in a coherent series in which each change
284 influences the following changes. For instance, to make his investment in a rotary-slasher profitable,
285 farmer B11 also integrated its use in subsequent changes, i.e. in the selection of spontaneous cover crops
286 (Figure 3f). Nelson and Winter (1982) and Labarthe (2010) described this as the “path dependency”
287 concept, according to which the range of possible technical solutions is restricted by past choices
288 (Sutherland et al., 2012), because solutions that cause disruption have an excessive cost, both cognitive
289 (the knowledge required, fixed representations) and financial (the need to make an investment in new
290 equipment profitable). Usually, changes considered by farmers as being “outside the path” were
291 eliminated by a cognitive experience. Conversely, some changes opened up new pathways to change,
292 e.g., widening the space between rows to allow compost ridging with a digger (farmer D03; Figure 3d)
293 and mechanized herbicide treatment (farmers B05 and B06; Figure 3e) allowed all three farmers to start
294 mechanical weeding using large machines such as rotary-slashers. In line with the “path dependency”
295 concept, our results suggest that past changes influence further changes by encouraging or discouraging
296 them. Our results did not allow us to conclude on several generic characteristics of the changes that led
297 to reinforce or to loosen the strength of the dependency. They rather supported the fact that a new
298 dependency is built at each change. For instance, enlarging rows allowed the use of large rotary slashers,
299 but this machinery harms the development of more weed-specific management practices, such as the
300 selection of spontaneous beneficial weeds.

301 **3.2.2. Knowledge and skill acquisition in farmers' trajectories**

302 Our surveys revealed that knowledge acquisition occurred throughout the farmers' trajectories via three
303 different types of concrete experience in learning processes, as identified by Chantre et al. (2014): (i)
304 simple testing of a new practice, (ii) formalized trials to test different technical characteristics of a
305 practice, and (iii) continuous learning through management of their farming system. First, all the farmers
306 tested a new practice on part of their cropping system before implementing it on a larger scale. If the
307 test was not conclusive, farmers abandoned the practice (e.g., farmers B05-B06, first test of mechanical
308 weeding, Figure 3e). This way of proceeding allowed farmers to learn how to manage a new practice in
309 their cropping system with a low resource commitment. It reduced the perceived risk of implementing
310 the practice. Meynard et al. (2012) describe this as "step-by-step design", corresponding to a trial and
311 error approach in the quest for solutions to an identified problem. Second, for complex changes entailing
312 modifications on a cropping system scale, farmers used more formal trials. They explored several
313 technical characteristics of a practice to find the most suitable combination of characteristics for their
314 own situation (Figure 3b, c, d, e). According to Chantre et al. (2014), trials provide appropriate technical
315 references in a specific context, and contribute to knowledge acquisition. Third, knowledge was also
316 acquired while the farmers were implementing a practice in their system. For instance, farmer B11
317 learned by rotary-slashing that it selected for *Commelia diffusa* (Figure 3f); farmer C09 said that he
318 learned about the effect of the lunar cycle on the growth and development of weeds (although, according
319 to Beeson (1946), this has not been clearly demonstrated) through continuous management of brush-
320 cutting (Figure 3a). They learned how their system responded to new practices by implementing them,
321 thereby enabling further improvement of the practices. As suggested by Meynard et al. (2012), adoption
322 and mastery of a technical system by a farmer is a prerequisite for its reassessment, and may lead to a
323 new change. Simple tests, formal trials and continuous learning last for different lengths of time before
324 the right solution is found. Indeed, many authors point out that acquisition of the knowledge and skills
325 required to construct trajectories is a gradual process (Bal et al., 2002; Chantre et al., 2015; Hill and
326 MacRae, 1996; Kolb, 1984; Meynard et al., 2012; Toffolini et al., 2017). However, if knowledge and
327 skills, and maybe even new values, are acquired throughout a gradual process, rupture changes may still
328 occur as long as farmers' capacity is sufficient to assess and face the loss of mastery. Rupture changes

329 might also occur after strong drivers even if a loss of mastery is at risk (e.g. drivers related to health
330 issues).

331 The skills and knowledge acquired for a specific practice can be a resource for other changes and can
332 be exploited in the future, e.g., farmers B05 and B06's first failure with mechanized mowing and first
333 widening of inter-rows was a source of knowledge for a new mechanized mowing system five years
334 later (Figure 3e). The same skills and knowledge can also be used to reassess other cropping systems
335 within the same farming system (see D03, D02 and D10's trajectories; Figure 3b, c, d). Thus, the
336 learning process is constructed on the basis of the farmer's point of view, i.e., on a farming system scale:
337 knowledge and skills can be mobilized from one part of the system to another. In that sense, we can
338 expect that a range of different systems on a farm multiplies the opportunities for acquiring experience
339 and knowledge to follow a trajectory of change.

340 To sum up, the acquisition of knowledge and skills plays a fundamental role in changing practices
341 because it has an unlocking effect. Change can occur as part of a continuous driving force and/or
342 irregular exploration of new options, but always with considerable concrete experience, as emphasized
343 by Chantre et al. (2015), Roussy et al. (2014) and Kolb (1984). In our sample, even when not in use,
344 knowledge and skills were not lost and could be exploited for other changes, at other times, perhaps in
345 other parts of the farming system. Knowledge and skills are acquired in a slow but dynamic learning
346 process that needs to engage the interest of farmers in acting, observing, reassessing and thinking about
347 new applications. These results reinforce the importance of the path used in farmers' trajectories where
348 practices and related knowledge/skills are constructed together and are inseparable.

349 **3.3.Redesigning farming systems in farmers' trajectories**

350 In this section, we analyze how cropping systems become more complex in farmers' trajectories. Indeed,
351 according to Toffolini et al. (2017), cropping systems need to be redesigned to produce agroecological
352 services likely to reduce the use of herbicides. Such a redesigning approach requires systemic adding of
353 complexity to the cropping system.

354 **3.3.1. Complexity is built within the trajectory**

355 Our results showed that successive simple changes could result in a redesigning of cropping systems
356 (Farmers C09 and B11; Figure 3a, f). Farmer C09 implemented simple changes throughout his trajectory
357 (Figure 3a, Table 1). Lastly, his pathway resulted in a more complex cropping system compared to the
358 original one: greater diversity, practice complementarity and increased biological regulation
359 (Malézieux, 2012). The system combined several farming operations: mulching, brush-cutting at a very
360 specific time and applying a herbicide only when no other option was available. His system amounted
361 to a break in the practices usually used by small-scale sugarcane growers, which are based on manual
362 weeding and the use of herbicides. Farmer C09's system resulted in low weed pressure, which made it
363 possible to apply only one fifth of the legal dose used by the majority of other small-scale sugarcane
364 growers. Farmer B11 also implemented only simple changes (Figure 3f). His trajectory resulted in a
365 more complex cropping system involving agroecological services in the form of a spontaneous plant
366 cover. Out of the seven banana growers in the watershed who decided not to destroy useful weeds, he
367 was the only one who did so by means of rotary-slashing (increasing cutting height – Figure 3f), which
368 he considered to be much more efficient than using a brush-cutter or herbicide spotting. These examples
369 suggest that the gradual adding of complexity to management practices through successive simple
370 changes can result in a more complex system, which produces agroecological services such as weed
371 control.

372 Different pathways can lead to the same goal. For instance, farmer B11's system (Figure 3f) tended
373 towards the objective expressed in the extension service's recommendation (i.e., maintaining a selected
374 plant cover to limit the development of weeds). The *Drymaria cordata* that he selected in his fields was
375 on the list of recommended plants. Yet, he did not modify his cropping system as recommended by the
376 extension services (i.e., planting and growing a cover crop; Table 1), but instead implemented successive
377 simple changes. He also maintained his path dependence by using a rotary-slasher, a new mechanical
378 way of maintaining the plant cover he had selected. Moreover, the simple changes implemented by this
379 farmer followed the same strategies as the majority of banana growers, i.e., mechanical weeding and not
380 destroying useful weeds (Table 1, section 3.1). Farmer B11's situation showed that unexpected pathways
381 developed by farmers could result in cropping systems that were comparable to those promoted by the

382 extension services. Moreover, mechanical weeding and not destroying useful weeds are simple changes
383 that can be considered as preliminary steps in farmers' trajectories, which may later lead to more
384 complex ones based on cover cropping. In order to confirm this result, it would have been interesting to
385 compare distinct trajectories that effectively led to the same weed management practices.

386 On the other hand, our results also showed that complex cropping systems could emerge as a result of a
387 complex systemic change on a cropping system scale (see section 2.1.1): farmer D03, B05, B06, D02
388 and D10's trajectories (Figure 3b, c, d, e). In the case of farmer D03, the systemic change did not deal
389 directly with weed control. For the other farmers (B05, B06, D02 and D10), the systemic changes were
390 used to transfer a weed management practice from one cropping system to another within the same
391 farming system. In these cases, the farmers had already gained experience in each cropping system and
392 had considered the possible transfer from one system to the other. The knowledge they had acquired
393 enabled them to foresee structural obstacles to this transfer (i.e., inter-row spacing for farmers B05-B06
394 and D02; compatibility between yam and intercrops for farmer D10). They explored different technical
395 characteristics of the practice and/or how to organize crop management to avoid the obstacles, thereby
396 enabling the transfer. Systemic changes on a cropping system scale using an exploratory approach thus
397 appeared to promote the transfer of practices between two distinct parts of the farming system, which
398 involved knowledge and skills previously developed independently, leading to more complex farming
399 systems.

400 Our results showed examples of complex systems that emerged gradually as the result of successive
401 simple changes, and occasionally and/or more rapidly through systemic changes on a cropping system
402 scale and an exploratory approach. This involves complex reasoning about the interaction between the
403 practice and several components of the farming system (technical characteristics of the practices, crop
404 management practices and organization of crop management over space and time). According to
405 Compagnone et al. (2008), this complex reasoning leads to a diversity of management between farms
406 and even on each farm. Meynard et al. (2012) suggested that innovation is not a linear but a ramified
407 process: "redesign of farming systems cannot be confined within a standardized approach" because it
408 limits farmers' capacity to adapt concepts to the diversity of their situations. Promoting a standardized

409 package appears to be incompatible with complex crop management practices. We therefore recommend
410 for our study site that when the aim is to promote the development of complex farming systems
411 integrating agroecological services, designers should take into account the diversity of on-farm realities
412 and paths that have resulted in a diversity of farming systems.

413 **3.3.2. Resource pooling without competition in collective actions favors complex changes**

414 Systemic changes on a cropping system scale (farmers B05, B06, D02 and D10, Figure 3b, e, f) occurred
415 within a group. For instance, farmers B05 and B06 redesigned mechanized weeding in their economic
416 interest group, farmer D02 explored brush-cutting with members of her marketing association, and
417 farmer D10 began intercropping yam with the three members of her mutual-aid system (i.e., a weekly
418 collective hand-weeding session). In these cases, other farmers from the collective were always cited as
419 the primary source of knowledge about the three steps in the learning process (sections 2.1.2 and 2.1.3).

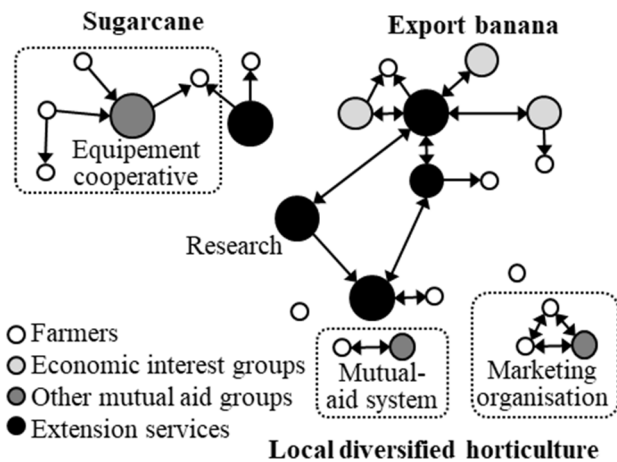
420 **(i) Alert Step:** The idea of the systemic change emerged in collective discussions through the sharing
421 of each participant's knowledge on the topic concerned. **(ii) Experiential Step:** Each participant tested
422 a different combination of the technical characteristics of the practices and/or organization of crop
423 management. When the combinations to be tested were split between the farmers, this collective
424 exploration multiplied the range of combinations tested at the same time. This collaboration increased
425 the probability of finding an appropriate solution and accelerated the process of exploration. **(iii)**
426 **Evaluation Step:** Lastly, the best combinations were identified by pooling the results. This collective
427 evaluation was a second knowledge sharing, including extra knowledge from each farmer's experience
428 which he/she had gained testing his/her combination. These findings supported the fact that collective
429 knowledge sharing supported each farmer in their personal knowledge acquisition (Chantre, 2011;
430 Kilelu et al., 2013; Meynard et al., 2012; Schneider et al., 2009). Our results suggested that knowledge
431 was multiplied by collective exploration due to the experience gained by the different farmers at the
432 same time (Kilelu et al., 2013). Thus, the knowledge acquired by one farmer could benefit changes
433 undertaken on another occasion and/or in another part of the farming system (see section 3.2.2), but also
434 on other farms in the watershed through knowledge sharing.

435 What these collectives had in common was the sharing of at least one resource involved in the
436 exploratory approach. For instance, farmer B05 and B06's economic interest groups shared plots, labor
437 force and weeding equipment; D02's marketing association proceeded with a pooled investment in
438 brush-cutters; and farmers from D10's mutual-aid system shared the labor force and equipment for
439 weeding. We identified other collective aid groups with no change on a cropping system scale, but
440 showing accelerated adoption of simpler changes. For instance, farmers B11, B02 and B07 established
441 an economic interest group and simultaneously and directly replaced the use of herbicides by brush-
442 cutters; farmer D03 shared the investment in a brush-cutter and rotary-slasher with a group of friends
443 for use in plantain. Thus, sharing appears to reinforce collective dynamics of change by facilitating
444 investment and empowering farmers to change. However, we also identified a counter-example in a
445 sugarcane equipment co-operative: in this case, competition between members for the shared resource
446 (harvesting equipment) during the harvest period threatened relations between the farmers, thereby
447 limiting interactions on possible changes in their practices. This situation was confirmed by the
448 sugarcane extension service. We thus recommend supporting and developing collective actions based
449 on the sharing of a resource, with no competition between users, to foster changes in practices in
450 territories.

451 Finally, farmers who pooled resources developed technical and organizational innovations that led to
452 changes. These results agree with Schneider et al. (2009), who called for more exchange spaces between
453 farmers, which in our context were spontaneously developed in response to a lack of adapted
454 institutional exchange spaces for these innovative farmers. In a different context, Ingram (2008) showed
455 that although many agronomist-farmer knowledge exchange encounters were characterized by an
456 imbalance of power, distrust, and the divergence of knowledge, other encounters provided a platform
457 for the facilitation of farmer learning in their transition to more sustainable practices. This supported the
458 need to develop innovation platforms (Kilelu et al., 2013) with interaction spaces dedicated to farmers
459 and to the interaction between farmers and extension and research.

460 **3.4. Support for changes in weed control practices on a territorial scale**

461 Sections 3.1, 3.2 and 3.3 showed how complex systems with low herbicide inputs emerged in farmers’
 462 trajectories but were still a minority in the Galion River watershed. As shown in section 3.3.2, the
 463 collective dimension of learning processes appeared to be one of the main reasons for the success of
 464 changes in practices due to the sharing of knowledge and experience. Here, we take a general view of
 465 collective interactions concerning weed control practices on a watershed scale.



466
 467 Figure 4: Schematic representation of relational networks that influenced weed management practices on a
 468 watershed scale. Arrows represent the influence of one actor over another for the learning of weed management
 469 practices and their evolution.

470 Figure 4 is a schematic representation of the relational networks that influenced changes in weed
 471 management in the watershed. It corresponds to a schematic simplified representation of Figure SI.A. It
 472 reveals that very few practices and/or knowledge were built collectively by exchanging capacities from
 473 one farming system to another (Figure 4). The only relations we identified between the farming systems
 474 were ensured by institutional stakeholders (i.e., research and extension services) and only concerned
 475 export banana and local diversified horticulture. Extension services played an unusual role in the
 476 farming system networks: the export banana extension services centralized the majority of relations we
 477 identified, while the sugarcane and diversified horticulture extension services influenced few farmers.
 478 Irrespective of the farming system, 21 farmers (64% of our sample) reported that the extension services
 479 were detached from their on-farm life. They described this disconnection as structural (i.e., lack of any
 480 real relation) and/or functional (i.e., inadequate recommendations or support). What is more, we

481 observed little farmer-to-farmer influence outside the above-mentioned mutual aid groups (section
482 3.3.2). This reveals unequal access to information, support and/or an absence of farmer-to-farmer
483 interactions concerning alternative weed control practices in the watershed, i.e., unequal opportunities
484 to share knowledge and experience both with other farmers and with extension services. Considering
485 that each farmer has interesting specific knowledge based on his/her trajectory (section 3.2.2) and that
486 the sharing of knowledge and experience favors changes in practices (section 3.3.2), we recommend
487 developing interactions between farming systems and within each farming system. In addition, bearing
488 in mind that the expertise of extension service supervisors is complementary to farmers' knowledge and
489 experience, we recommend considering the two resources jointly to support more ecological weed
490 control on a watershed scale.

491 According to Lewin and Grabbe (1945), the process of change modifies the value system of an
492 individual. In this case, the individual needs to refer to a group of individuals in order to
493 establish a new value system. The group acts as a reducer of uncertainty, if the individual can
494 freely express the perceptions that the change modifies in their value system. Recent studies of
495 farmer groups showed that farmers discussing their practices within peer groups are more
496 innovative if the groups have access to sources of external knowledge (Dolinska and d'Aquino,
497 2016). Indeed, farmer groups provide access to knowledge that they consider as legitimate.

498 According to Daouda (2015) and Dolinska and d'Aquino (2016), agricultural experience is a
499 determining factor in the legitimacy that farmers will give to the discourse of an individual.
500 This explains why farmers prefer to receive advice from their peers. In addition, small groups
501 develop common codes, vocabularies and habits that improve understanding among members
502 (Dionnet et al., 2013). In the experiment conducted by Goulet (2013), the author observed the
503 behavior of farmers in a group, and showed that farmers describe their experiences using
504 generic objects that are understandable by the other farmers, with properties widely, commonly
505 and implicitly defined. On the other hand, the group of peers may also generate locking
506 phenomena against change, because of the risk of exclusion, arising from farmers who innovate

507 outside the system of values shared by the group. On this point, sociologists have shown that
508 social integration is a key condition for changes. For instance, Houdart et al. (2011) discussed
509 the tolerance of practice differences between farmers. In our setting, friendship and neighborly
510 relationships seemed to be a factor of confidence between diversified farmers (friendship
511 relationships expressed by farmers D01 and D03 (Code “.Ami” in Figure SI.A), neighborly
512 relationships expressed by farmers D06, D08, and D10 (Code “.Vois” in Figure SI.A). This
513 means that in these groups, relationships could be multiple, at the same time personal and
514 professional, inducing multiplex ties as identified by Houdart et al. (2011) while analyzing a
515 farmer social network in another watershed in the French West Indies. In our case, it may have
516 been that discussions were facilitated, and the risk of social exclusion was lower because of
517 nonprofessional relationships involved in friendship or neighborly relationship networks. This
518 setting necessarily induced a smaller relational network due to its nature, or to friendship, but
519 facilitated changes because of confident and honest discussions, exchanges between peers. Such
520 a setting made it possible for other farmers to discuss problems. Our results showed that in
521 banana and sugarcane system networks, farmers B07 and C09 concentrated a large number of
522 influential relationships (Figure SI.A). This might have induced a new social positioning after
523 their changes, in particular the status of “pioneers” according to (Rogers, 2010). Both gained in
524 recognition by their peers and shared their experiences within their network (Figure SI.A). This
525 provided the possibility for other farmers from the network to exchange about their problems,
526 from an agronomic viewpoint, but also potentially from a sociological point of view while
527 gaining from the experience of the “pioneer”. The discussion about these different situations
528 shows that the quality of the relational network is core to the acceptance of changes. These
529 different results showed that a professional network might be associated with nonprofessional
530 relationships to favor the social recognition of changes in practice. Thus, innovation platforms
531 such as those proposed by Kilelu et al. (2013) would gain in value by facilitating social

532 interactions between a large diversity of farmers, while making it possible for them to exchange
533 on more than just technical and professional issues.

534 **4. Conclusion**

535 We showed that farmers' trajectories play a central role in changing farming systems. As a result, we
536 recommend that these trajectories be considered as subjects, not only of observation, but also of design.
537 We showed that trajectories are the places where changes of practice are learnt, and that performing
538 simple step-by-step changes makes it possible to gradually learn complexity in cropping system design.
539 As a result, we suggest that the recommendations made by extension services be improved by proposing
540 a range of potential sustainable systems and possible paths of simple step-by-step changes that could
541 help in learning those sustainable systems. Conversely, promoting a standardized practice package
542 appears to be incompatible with the development of complex sustainable cropping systems. Our analysis
543 also showed that social interactions between farmers are of substantial importance for making changes
544 effective on farms. Resource pooling appeared to be a response from farmers for co-innovation that
545 favors innovation as long as there is no competition for the resource. We recommend that such collective
546 actions should be supported within innovation platforms and that research and extension services should
547 work with farmers on developing such organizations to foster the development of innovative cropping
548 systems. In our context, this will mean building interaction spaces between farmers from the different
549 supply chains.

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