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

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Abstract

Herbicides used in agriculture pollute water worldwide. However, several weed management alternatives can reduce herbicide applications. The understanding of interactions between agronomics and the learning and social processes that favor changes in practices on a territorial scale is still far from complete. Despite the call for systemic change approaches, most studies are still based on technology transfer. Research and extension services provide references on alternative weed management practices and promote their use among farmers. We surveyed 33 farmers in a 45 km² tropical catchment plus five institutional extension services. We analyzed changes in weed management practices on the 33 farms belonging to three different agricultural chains: local diversified horticulture, sugarcane, and export banana. For each change, we analyzed the learning processes and the networks involved in information exchanges. First, we show that the complexity of the practices promoted by extension services limits their adoption. Second, we show that simple practices adopted by farmers are part of a slow trajectory of change involving the gradual acquisition of knowledge. A redesign of cropping systems can emerge as the result of a gradual adding of complexity in practices and/or a specific systemic change on a cropping system scale. Sharing knowledge and resources in a non-competitive way speeds up changes among farmers sharing resources and promotes the redesigning of cropping systems. Third, we show that the structure and functioning of relational networks limit changes in practices on a watershed scale. We thus recommend that innovation design should incorporate co-designing of the pathway of change, by designing a succession of simple changes rather than a complex final system only. We recommend including non-competitive resource pooling among farmers in the co-designing of innovation.

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

Declarations of interest: none

1. Introduction

Pests and weeds have negative impacts on crop productivity and quality worldwide. Farmers use various techniques to protect their crops and stabilize their yields, one of the most problematic for the environment being the use of pesticides. Thus, shifting to pesticide-free agricultural practices remains a challenge. To that end, agronomists have sought ways of accelerating and facilitating cropping practice changes among farmers. Considerable research efforts have been made by researchers, farmers, and extension workers to find new crop protection strategies and techniques, and to understand their interactions (for a review see Schut et al. (2014)). Schut et al. (2014) found that the majority of these efforts focused on transferring a technology from research or from an extension service to farmers, while more systemic approaches (agricultural knowledge and information systems, agricultural innovation systems) are required to enhance the resilience of crop protection systems. Accordingly, Wigboldus et al. (2016) explained that the dominant methods for scaling innovations are empirical and based on the premise "find out what works in one place and do more of the same in another place". This approach simplifies the complex processes of practice changes. On the one hand, the technology transfer approach highlighted the effects of the technical characteristics of innovation, the characteristics of the farm, the farmers themselves, and other exogenous, unmanageable factors (e.g. socio-economic and pedo-climatic contexts) in the adoption of innovations (Blazy et al., 2009a; Blazy et al., 2009b; Roussy et al., 2014; Schut et al., 2014). On the other hand, Kilelu et al. (2014) showed that because learning in agricultural innovation processes is dynamic, static notions of demand articulation and related support are inadequate. The more recent knowledge and information systems approach has broadened knowledge on the factors that influence practice changes. Sutherland et al. (2012) conceptualized changes on a farm scale in a dynamic way. They showed that major changes on a farm follow a pattern of "trigger events" while minor changes are made incrementally, with both following a path dependency. Lamine (2011) and Chantre and Cardona (2014) showed that changes in cropping systems rely on an individual learning process within a farmer's sociotechnical trajectory. Klerkx et al. (2012) showed that innovation in agricultural systems goes beyond seeing research as the main input to change and innovation, and recognises that innovation emerges from complex interactions between multiple actors. Learning processes involve personal and external information originating from the farmer's experience and social interactions (Chantre, 2011; Chantre et al., 2015; Ingram, 2008; Schneider et al., 2009). Compagnone and Hellec (2015), Lowitt et al. (2015) and Saint Ville et al. (2016) highlighted the importance of social interactions in the territorial dynamics of change in different contexts and showed that collective sharing of local specific knowledge fosters the design and spread of innovative practices. Therefore, knowledge exchange between different stakeholders appears to be a key triggering event for practice changes. But what kind of changes? Qualifying changes has always been a tricky issue, especially as changes might be seen as subjective. Nevertheless, classifying modified systems according to conventional system references was proposed by Hill and MacRae (1996) and Altieri and Rosset (1996) in order to assess sustainability. They showed that changes could be of an efficiency, substitutive, or redesign nature. According to Sutherland et al. (2012), two types of changes exist, minor and major, while for Aubry and Michel-Dounias (2006) changes might be classified according to the decision level they involve: tactical, operational, or strategic.

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

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

2. Materials and methods

2.1. Theoretical framework

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

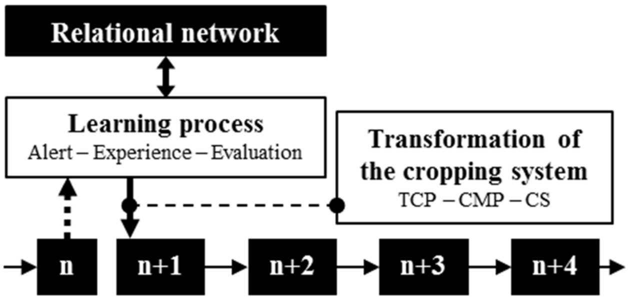

Figure 1: The theoretical analysis framework elaborated (n = successive states of the cropping system; dotted arrow = exploration of new solutions through a learning process; double-headed arrow = interaction with the dialogue network within the learning process; solid arrow = implementation of a change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

2.1.1. Qualifying cropping system changes within farmers' trajectories

Our framework conceptualized farmers' trajectories as a succession of stable phases during which management practices remained unchanged, and technical changes that took place between the stable phases (Figure 1). Each technical change in the cropping system could have been related to a classification in existing frameworks (Hill and MacRae, 1996; Sutherland et al., 2012). Nevertheless, such classifications might seem rather conceptual for farmers. This is why, in our framework, each technical change in cropping systems could be described by related transformations at three different levels of cropping system management (Doré and Meynard, 2006; Sebillotte, 1990; Shrestha and Clements, 2003) - Figure 1: (i) The modification of a technical characteristic of a practice. The change is simple because the farmer modifies only one technical aspect of a practice (e.g. dose applied, tillage depth, mowing height, molecule used, tool used). (ii) The modification of a crop management practice (e.g. replacement of chemical weeding by manual or mechanical weeding). The change is slightly more complex because the farmer modifies the crop management practice and all its associated technical parameters. (iii) The modification of the cropping system. This includes modifications to the nature of crops or their organization over space and time (e.g. diversifying crops, replacing a crop by another, enlarging the inter-row of perennial crops, intercropping, modifying a planting date). This also includes the organization of management practices over space and time (e.g. integrating a new practice in crop management, modifying a treatment/operation date, implementing a change in a practice that automatically entails other changes in other practices). These changes are complex because the farmer modifies several crop management practices, their technical characteristics and their organization over space and time in a systemic way. Such changes could be seen as loosely coupled systems according to Coughenour (2003), because the system is modified in its different components while aiming to achieve several goals. On the other hand, technical and practical modifications are closer to tightly coupled systems where most components of the systems remain unmodified by the change.

2.1.2. Individual learning processes

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

2.1.3. Collective learning processes

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

2.2. Study site

The study was conducted in the 44.5 km² Galion River watershed, Martinique, French West Indies (61°4.4004′W/14°36.5352′ N), whose elevation ranges from 0 to 694 m asl. The watershed is divided into three agroecological zones (Della Rossa et al., 2017; Mottes et al., 2019)): **(i)** An upstream mountainous zone with steep slopes (> 80%), abundant annual rainfall (3,500 to 4,000 mm.y^{-1}), with mainly small mixed farms, livestock and traditional crops, with a utilized agricultural area (UAA) of less than 4 ha,. **(ii)** A hilly zone with a more gently sloping topography (35%), annual rainfall of about 2,500 mm.y^{-1}, characterized by banana (*Musa* spp.) farms: UAA from 4 to 150 ha and small mixed farms. **(iii)** A downstream floodplain with a relatively flat topography (slopes < 35%) and low annual rainfall (1,500 mm.y^{-1}), characterized by small sugarcane (*Saccharum officinarum*) farms (UAA < 15 ha), one large industrial sugarcane farm and some large banana farms (UAA > 50 ha).

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

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

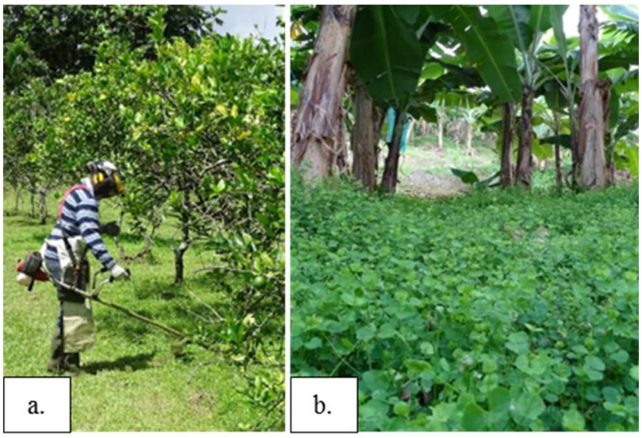

Figure 2: Examples of alternative weed management practices in the Galion River watershed (a. brush-cutting in a citrus orchard; b. cover-cropping in banana).

2.3. Implementation of the survey

The same person conducted semi-structured interviews with all 33 farmers and five supervisors from the agricultural and environmental organizations mentioned by the farmers as having an influence on their trajectory. We surveyed farms with the three main agricultural sectors: export bananas, sugarcane and local diversified horticulture according to the 6 farm types identified by Raimbault (2014) in the watershed (export banana, large sugarcane farm, small sugarcane farm, plantain banana, floral horticulture and other fruit, tuber and vegetable farmers). Our objective was to survey at least 10 farmers in each main sector to obtain a balanced sample between agricultural sectors. Only one floral horticulturist and one large sugarcane farm were present in the watershed, and were selected to be surveyed to represent their farm type in their agricultural sector. The other farmers were selected randomly from the list established by Raimbault (2014). If the farmer was unreachable, we contacted another until we managed to survey 10 farmers per farming system, which we did not manage for sugarcane farms. When it was possible, we also surveyed farmers whom we had already identified as having an influence on the evolution of their weed management practices (we added farmers B06, B07, C07, C09 and D05). We did this to identify key farmers involved in processes of change on a territorial scale. However, we limited the surveyed farmers to those located in the watershed. Lastly, we interviewed 12 banana farmers (eight large-scale and three small-scale farms; noted **B**), nine sugarcane farmers (one large-scale and eight small-scale farms; noted **C**) and 12 farmers with diversified farming systems (one large-scale flower farm, one large-scale plantain farm, one small plantain farm, one small citrus farm, and eight small tuber and horticulture farms; noted **D**). The characteristics of the farmers are summarized in Supplementary Table SI.A. We asked questions about weed management practices over the five years preceding the survey. The interviews were used to describe the farmer's sociotechnical trajectory. Each change **(i)** was qualified according to the framework illustrated in section 2.1.1; **(ii)** according to the framework described in section 2.1.2; the elements from the alert, experience and evaluation steps of the learning process of each change were discussed and summed up with each farmer; and **(iii)** in the meantime, for each step in the Kolb cycle, relations with the network were surveyed and classified according to information sources, representatives and type of interaction for the three steps of the learning process (section 2.1.3).

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

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

3. Results and discussion

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

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

	Transfer pathway Strategy	Description of the change	Required modification in Technical charact. of the practices (TCP)	 Crop management practices (CMP)	 Cropping system (CS)	Adoption rate (Number of farmers)
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%**
	Farmers Improve traditional practices	**Wide range of changes (hand/mechanical weeding, tillage or intercropping) with variable modifications in TCP, CMP and/or CS.**				
		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.

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

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

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

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

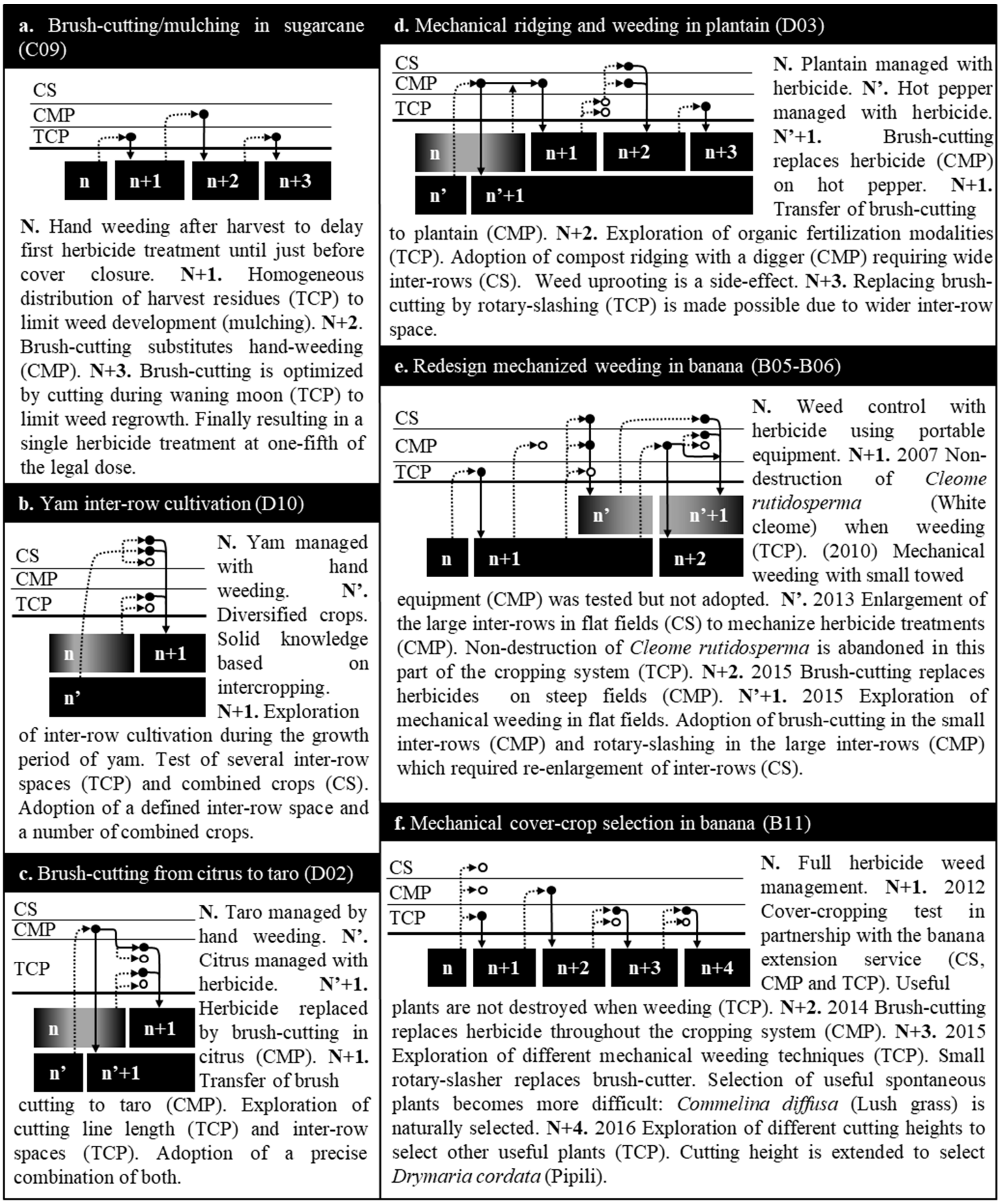

Figure 3: Examples of changes in weed control practices in farmers' trajectories. (N and N' = two distinct cropping systems on the same farm; dotted arrows = exploration; solid arrows = implementation in the cropping system; black dots = implemented changes; empty dots = abandoned changes; each change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

3.2.1. Successive and coherent changes in farmers' trajectories

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

3.2.2. Knowledge and skill acquisition in farmers' trajectories

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

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

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

3.3.Redesigning farming systems in farmers' trajectories

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

3.3.1. Complexity is built within the trajectory

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

Different pathways can lead to the same goal. For instance, farmer B11's system (Figure 3f) tended towards the objective expressed in the extension service's recommendation (i.e., maintaining a selected plant cover to limit the development of weeds). The *Drymaria cordata* that he selected in his fields was on the list of recommended plants. Yet, he did not modify his cropping system as recommended by the extension services (i.e., planting and growing a cover crop; Table 1), but instead implemented successive simple changes. He also maintained his path dependence by using a rotary-slasher, a new mechanical way of maintaining the plant cover he had selected. Moreover, the simple changes implemented by this farmer followed the same strategies as the majority of banana growers, i.e., mechanical weeding and not destroying useful weeds (Table 1, section 3.1). Farmer B11's situation showed that unexpected pathways developed by farmers could result in cropping systems that were comparable to those promoted by the extension services. Moreover, mechanical weeding and not destroying useful weeds are simple changes that can be considered as preliminary steps in farmers' trajectories, which may later lead to more complex ones based on cover cropping. In order to confirm this result, it would have been interesting to compare distinct trajectories that effectively led to the same weed management practices.

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

Our results showed examples of complex systems that emerged gradually as the result of successive simple changes, and occasionally and/or more rapidly through systemic changes on a cropping system scale and an exploratory approach. This involves complex reasoning about the interaction between the practice and several components of the farming system (technical characteristics of the practices, crop management practices and organization of crop management over space and time). According to Compagnone et al. (2008), this complex reasoning leads to a diversity of management between farms and even on each farm. Meynard et al. (2012) suggested that innovation is not a linear but a ramified process: "redesign of farming systems cannot be confined within a standardized approach" because it limits farmers' capacity to adapt concepts to the diversity of their situations. Promoting a standardized package appears to be incompatible with complex crop management practices. We therefore recommend for our study site that when the aim is to promote the development of complex farming systems integrating agroecological services, designers should take into account the diversity of on-farm realities and paths that have resulted in a diversity of farming systems.

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

Systemic changes on a cropping system scale (farmers B05, B06, D02 and D10, Figure 3b, e, f) occurred within a group. For instance, farmers B05 and B06 redesigned mechanized weeding in their economic interest group, farmer D02 explored brush-cutting with members of her marketing association, and farmer D10 began intercropping yam with the three members of her mutual-aid system (i.e., a weekly collective hand-weeding session). In these cases, other farmers from the collective were always cited as the primary source of knowledge about the three steps in the learning process (sections 2.1.2 and 2.1.3). **(i) Alert Step:** The idea of the systemic change emerged in collective discussions through the sharing of each participant's knowledge on the topic concerned. **(ii) Experiential Step:** Each participant tested a different combination of the technical characteristics of the practices and/or organization of crop management. When the combinations to be tested were split between the farmers, this collective exploration multiplied the range of combinations tested at the same time. This collaboration increased the probability of finding an appropriate solution and accelerated the process of exploration. **(iii) Evaluation Step:** Lastly, the best combinations were identified by pooling the results. This collective evaluation was a second knowledge sharing, including extra knowledge from each farmer's experience which he/she had gained testing his/her combination. These findings supported the fact that collective knowledge sharing supported each farmer in their personal knowledge acquisition (Chantre, 2011; Kilelu et al., 2013; Meynard et al., 2012; Schneider et al., 2009). Our results suggested that knowledge was multiplied by collective exploration due to the experience gained by the different farmers at the same time (Kilelu et al., 2013). Thus, the knowledge acquired by one farmer could benefit changes undertaken on another occasion and/or in another part of the farming system (see section 3.2.2), but also on other farms in the watershed through knowledge sharing.

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

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

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

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

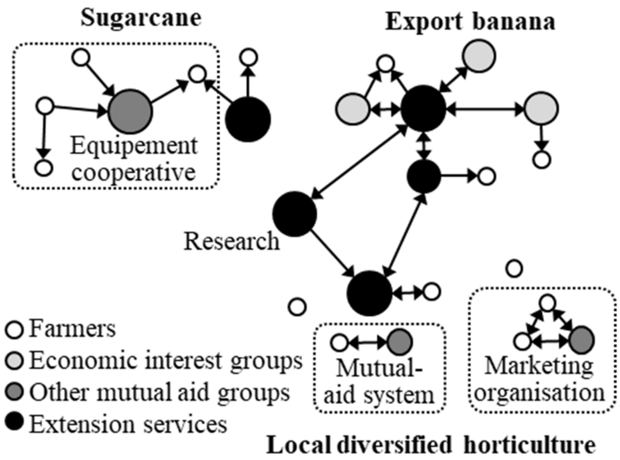

Figure 4: Schematic representation of relational networks that influenced weed management practices on a watershed scale. Arrows represent the influence of one actor over another for the learning of weed management practices and their evolution.

Figure 4 is a schematic representation of the relational networks that influenced changes in weed management in the watershed. It corresponds to a schematic simplified representation of Figure SI.A. It reveals that very few practices and/or knowledge were built collectively by exchanging capacities from one farming system to another (Figure 4). The only relations we identified between the farming systems were ensured by institutional stakeholders (i.e., research and extension services) and only concerned export banana and local diversified horticulture. Extension services played an unusual role in the farming system networks: the export banana extension services centralized the majority of relations we identified, while the sugarcane and diversified horticulture extension services influenced few farmers. Irrespective of the farming system, 21 farmers (64% of our sample) reported that the extension services were detached from their on-farm life. They described this disconnection as structural (i.e., lack of any real relation) and/or functional (i.e., inadequate recommendations or support). What is more, we observed little farmer-to-farmer influence outside the above-mentioned mutual aid groups (section 3.3.2). This reveals unequal access to information, support and/or an absence of farmer-to-farmer interactions concerning alternative weed control practices in the watershed, i.e., unequal opportunities to share knowledge and experience both with other farmers and with extension services. Considering that each farmer has interesting specific knowledge based on his/her trajectory (section 3.2.2) and that the sharing of knowledge and experience favors changes in practices (section 3.3.2), we recommend developing interactions between farming systems and within each farming system. In addition, bearing in mind that the expertise of extension service supervisors is complementary to farmers' knowledge and experience, we recommend considering the two resources jointly to support more ecological weed control on a watershed scale.

According to Lewin and Grabbe (1945), the process of change modifies the value system of an individual. In this case, the individual needs to refer to a group of individuals in order to establish a new value system. The group acts as a reducer of uncertainty, if the individual can freely express the perceptions that the change modifies in their value system. Recent studies of farmer groups showed that farmers discussing their practices within peer groups are more innovative if the groups have access to sources of external knowledge (Dolinska and d'Aquino, 2016). Indeed, farmer groups provide access to knowledge that they consider as legitimate. According to Daouda (2015) and Dolinska and d'Aquino (2016), agricultural experience is a determining factor in the legitimacy that farmers will give to the discourse of an individual. This explains why farmers prefer to receive advice from their peers. In addition, small groups develop common codes, vocabularies and habits that improve understanding among members (Dionnet et al., 2013). In the experiment conducted by Goulet (2013), the author observed the behavior of farmers in a group, and showed that farmers describe their experiences using generic objects that are understandable by the other farmers, with properties widely, commonly and implicitly defined. On the other hand, the group of peers may also generate locking phenomena against change, because of the risk of exclusion, arising from farmers who innovate outside the system of values shared by the group. On this point, sociologists have shown that social integration is a key condition for changes. For instance, Houdart et al. (2011) discussed the tolerance of practice differences between farmers. In our setting, friendship and neighborly relationships seemed to be a factor of confidence between diversified farmers (friendship relationships expressed by farmers D01 and D03 (Code ".Ami" in Figure SI.A), neighborly relationships expressed by farmers D06, D08, and D10 (Code ".Vois" in Figure SI.A). This means that in these groups, relationships could be multiple, at the same time personal and professional, inducing multiplex ties as identified by Houdart et al. (2011) while analyzing a farmer social network in another watershed in the French West Indies. In our case, it may have been that discussions were facilitated, and the risk of social exclusion was lower because of nonprofessional relationships involved in friendship or neighborly relationship networks. This setting necessarily induced a smaller relational network due to its nature, or to friendship, but facilitated changes because of confident and honest discussions, exchanges between peers. Such a setting made it possible for other farmers to discuss problems. Our results showed that in banana and sugarcane system networks, farmers B07 and C09 concentrated a large number of influential relationships (Figure SI.A). This might have induced a new social positioning after their changes, in particular the status of "pioneers" according to (Rogers, 2010). Both gained in recognition by their peers and shared their experiences within their network (Figure SI.A). This provided the possibility for other farmers from the network to exchange about their problems, from an agronomic viewpoint, but also potentially from a sociological point of view while gaining from the experience of the "pioneer". The discussion about these different situations shows that the quality of the relational network is core to the acceptance of changes. These different results showed that a professional network might be associated with nonprofessional relationships to favor the social recognition of changes in practice. Thus, innovation platforms such as those proposed by Kilelu et al. (2013) would gain in value by facilitating social interactions between a large diversity of farmers, while making it possible for them to exchange on more than just technical and professional issues.

4. Conclusion

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

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5. References

Altieri, M.A., Rosset, P., 1996. Agroecology and the conversion of large-scale conventional systems to sustainable management. Int. J. environ. stud. 50, 165-185.

Aubry, C., Michel-Dounias, I., 2006. Systèmes de culture et décisions techniques dans l'exploitation agricole, in: Doré, T., Le Bail, M., Martin, P., Ney, B., Roger-Estrade, J. (Eds.), L'agronomie aujourd'hui, Quae ed, Paris, pp. 57-75.

Bal, P., Castellanet, C., Pillot, D., 2002. Accompagner le développement des exploitations agricoles : faciliter l'émergence et la diffusion des innovations, Mémento de l'agronome. CIRAD, Montpellier, France, pp. 373-405.

Beeson, C.F.C., 1946. The Moon and Plant Growth. Nature 158, 572-573, https://doi.org/10.1038/158572a0.

Blazy, J.-M., Dorel, M., Salmon, F., Ozier-Lafontaine, H., Wery, J., Tixier, P., 2009a. Model-based assessment of technological innovation in banana cropping systems contextualized by farm types in Guadeloupe. Eur. J. Agron. 31, 10-19, https://doi.org/10.1016/j.eja.2009.02.001.

Blazy, J.-M., Ozier-Lafontaine, H., Doré, T., Thomas, A., Wery, J., 2009b. A methodological framework that accounts for farm diversity in the prototyping of crop management systems. Application to banana-based systems in Guadeloupe. Agric. Syst. 101, 30-41, https://doi.org/10.1016/j.agsy.2009.02.004.

Cattan, P., Charlier, J.B., Clostre, F., Letourmy, P., Arnaud, L., Gresser, J., Jannoyer, M., 2019. A conceptual model of organochlorine fate from a combined analysis of spatial and mid- to long-term trends of surface and ground water contamination in tropical areas (FWI). Hydrol. Earth Syst. Sci. 23, 691-709, https://doi.org/10.5194/hess-23-691-2019.

Chantre, E., 2011. Farmers' learning processes in implementing low-input field crop agriculture : Case study of Champagne Berrichonne (Indre, France) during the years 1985-2010. AgroParisTech.

Chantre, E., Cardona, A., 2014. Trajectories of French Field Crop Farmers Moving Toward Sustainable Farming Practices: Change, Learning, and Links with the Advisory Services. Agroecol. Sust. Food. 38, 573-602, https://doi.org/10.1080/21683565.2013.876483.

Chantre, E., Cerf, M., Le Bail, M., 2015. Transitional pathways towards input reduction on French field crop farms. Int. J. of Agric. Sustain. 13, 69-86, https://doi.org/10.1080/14735903.2014.945316.

Chantre, É., Le Bail, M., Cerf, M., 2014. Une diversité de configurations d'apprentissage en situation de travail pour réduire l'usage des engrais et pesticides agricoles. Activités 11.

Clostre, F., Letourmy, P., Lesueur-Jannoyer, M., 2017. Soil thresholds and a decision tool to manage food safety of crops grown in chlordecone polluted soil in the French West Indies. Environ. Pollut. 223, 357-366, https://doi.org/10.1016/j.envpol.2017.01.032.

Compagnone, C., Hellec, F., 2015. Farmers' Professional Dialogue Networks and Dynamics of Change: The Case of ICP and No-Tillage Adoption in Burgundy (France). Rural Sociol. 80, 248-273, https://doi.org/10.1111/ruso.12058.

Compagnone, C., Hellec, F., Macé, K., Morlon, P., Munier-Jolain, N., Quéré, L., 2008. Raisonnement des pratiques et des changements de pratiques en matière de désherbage: regards agronomique et sociologique à partir d'enquêtes chez des agriculteurs. Innov. agron. 3, 89-105.

Coughenour, C.M., 2003. Innovating Conservation Agriculture: The Case of No-Till Cropping. Rural Sociol. 68, 278-304, https://doi.org/10.1111/j.1549-0831.2003.tb00138.x.

Crabit, A., Cattan, P., Colin, F., Voltz, M., 2016. Soil and river contamination patterns of chlordecone in a tropical volcanic catchment in the French West Indies (Guadeloupe). Environ. Pollut. 212, 615-626, https://doi.org/10.1016/j.envpol.2016.02.055.

Daouda, O., 2015. L'adaptation de l'agriculture au changement et à la variabilité climatiques au Québec: un processus de diffusion des innovations.

Deffontaines, L., Mottes, C., 2017. Appui au pilotage et au suivi du dispositif d'instrumentation pour la caractérisation des pesticides du bassin versant pilote martiniquais du Galion. Cirad - ODE, Martinique, p. 55.

Della Rossa, P., Jannoyer, M., Mottes, C., Plet, J., Bazizi, A., Arnaud, L., Jestin, A., Woignier, T., Gaude, J.-M., Cattan, P., 2017. Linking current river pollution to historical pesticide use: Insights for territorial management? Sci. Tot. Environ. 574, 1232-1242, https://doi.org/10.1016/j.scitotenv.2016.07.065.

Dionnet, M., Daniell, K.A., Imache, A., Von Korff, Y., Bouarfa, S., Garin, P., Jamin, J.-Y., Rollin, D., Rougier, J.E., 2013. Improving participatory processes through collective simulation: use of a community of practice. Ecology and Society 18 16, https://doi.org/10.5751/ES-05244-180136.
Dolinska, A., d'Aquino, P., 2016. Farmers as agents in innovation systems. Empowering farmers for innovation through communities of practice. Agric. Syst. 142, 122-130, https://doi.org/10.1016/j.agsy.2015.11.009.
Doré, T., Meynard, J.-M., 2006. Introduction, in: Doré, T., Le Bail, M., Martin, P., Ney, B., Roger-Estrade, J. (Eds.), L'agronomie aujourd'hui, Quae ed. Quae, Paris, pp. 33-56.
Goulet, F., 2013. Narratives of experience and production of knowledge within farmers' groups. J. Rural Stud. 32, 439-447, https://doi.org/10.1016/j.jrurstud.2013.09.006.
Hill, S.B., MacRae, R.J., 1996. Conceptual Framework for the Transition from Conventional to Sustainable Agriculture. J. Sustain. Agric. 7, 81-87, https://doi.org/10.1300/J064v07n01_07.
Houdart, M., Bonin, M., Compagnone, C., 2011. Social and spatial organisation–assessing the agroecological changes on farms: case study in a banana-growing area of Guadeloupe. Int. J. Agric. Res. Gov. Ecol. 9, 15-30.
Ingram, J., 2008. Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. Agriculture and Human Values 25, 405-418, https://doi.org/10.1007/s10460-008-9134-0.
Ingram, J., 2010. Technical and Social Dimensions of Farmer Learning: An Analysis of the Emergence of Reduced Tillage Systems in England. J. Sustain. Agric. 34, 183-201, https://doi.org/10.1080/10440040903482589.
Kilelu, C.W., Klerkx, L., Leeuwis, C., 2013. Unravelling the role of innovation platforms in supporting co-evolution of innovation: Contributions and tensions in a smallholder dairy development programme. Agric. Syst. 118, 65-77, https://doi.org/10.1016/j.agsy.2013.03.003.
Kilelu, C.W., Klerkx, L., Leeuwis, C., 2014. How Dynamics of Learning are Linked to Innovation Support Services: Insights from a Smallholder Commercialization Project in Kenya. J. Agric. Educ. Ext. 20, 213-232, https://doi.org/10.1080/1389224X.2013.823876.
Kilpatrick, S., Johns, S., 2003. How farmers learn: Different approaches to change. J. Agric. Educ. Ext. 9, 151-164, https://doi.org/10.1080/13892240385300231.
Klerkx, L., Schut, M., Leeuwis, C., Kilelu, C., 2012. Advances in Knowledge Brokering in the Agricultural Sector: Towards Innovation System Facilitation. IDS Bull. 43, 53-60, https://doi.org/10.1111/j.1759-5436.2012.00363.x.
Kolb, D.A., 1984. Experiential learning: Experience as the source of learning and development. FT press.
Labarthe, P., 2010. Services immatériels et verrouillage technologique. Le cas du conseil technique aux agriculteurs. Gazette du Palais 44, 173-196.
Lamine, C., 2011. Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. J. Rural Stud. 27, 209-219, https://doi.org/10.1016/j.jrurstud.2011.02.001.
Lazega, E., 1994. Analyse de réseaux et sociologie des organisations. Rev. fr. sociol., 293-320.
Lewin, K., Grabbe, P., 1945. Conduct, Knowledge, and Acceptance of New Values. J. Soc. Issues 1, 53-64, https://doi.org/10.1111/j.1540-4560.1945.tb02694.x.
Lowitt, K., Hickey, G.M., Saint Ville, A., Raeburn, K., Thompson-Colón, T., Laszlo, S., Phillip, L.E., 2015. Factors affecting the innovation potential of smallholder farmers in the Caribbean Community. Reg. Environ. Change 15, 1367-1377, https://doi.org/10.1007/s10113-015-0805-2.
Malézieux, E., 2012. Designing cropping systems from nature. Agron. Sustain. Dev. 32, 15-29, https://doi.org/10.1007/s13593-011-0027-z.
Meynard, J.-M., Dedieu, B., Bos, A.P., 2012. Re-design and co-design of farming systems. An overview of methods and practices, in: Darnhofer, I., Gibbon, D., Dedieu, B. (Eds.), Farming Systems Research into the 21st Century: The New Dynamic. Springer Netherlands, Dordrecht, pp. 405-429.
Mottes, C., Deffontaines, L., Charlier, J.B., Comte, I., Della Rossa, P., Lesueur-Jannoyer, M., Woignier, T., Adele, G., Tailame, A.-L., Arnaud, L., Plet, J., Rangon, L., Bricquet, J.-P., Cattan, P., 2019. Spatio-temporal variability of water pollution by chlordecone at the watershed scale: what insights for the management of polluted territories? Environ. Sci. Pollut. Res., https://doi.org/10.1007/s11356-019-06247-y.

Mottes, C., Lesueur Jannoyer, M., Le Bail, M., Guene, M., Carles, C., Malezieux, E., 2017. Relationships between past and present pesticide applications and pollution at a watershed outlet: The case of a horticultural catchment in Martinique, French West Indies. Chemosphere 184, 762-773, https://doi.org/10.1016/j.chemosphere.2017.06.061.

Multigner, L., Kadhel, P., Rouget, F., Blanchet, P., Cordier, S., 2016. Chlordecone exposure and adverse effects in French West Indies populations. Environ. Sci. Pollut. Res. 23, 3-8, https://doi.org/10.1007/s11356-015-4621-5.

Nelson, R.R., Winter, J.M., 1982. An evolutionary theory of economic change. harvard university press.

Raimbault, M., 2014. Diagnostic des pratiques phytosanitaires à l'échelle d'un bassin versant et pression potentielle sur la qualité de l'eau de rivière. Cas du bassin versant du Galion, Martinique, AgroParisTech. AgroParisTech, Paris, p. 68.

Rogers, E.M., 2010. Diffusion of innovations. Simon and Schuster.

Roussy, C., Ridier, A., Chaïb, K., 2014. Adoption d'innovations par les agriculteurs : rôle des perceptions et des préférences, 8. Journées de recherches en sciences sociales (JRSS), Grenoble, France, p. np.

Saint Ville, A.S., Hickey, G.M., Locher, U., Phillip, L.E., 2016. Exploring the role of social capital in influencing knowledge flows and innovation in smallholder farming communities in the Caribbean. Food Secur. 8, 535-549, https://doi.org/10.1007/s12571-016-0581-y.

Schneider, F., Fry, P., Ledermann, T., Rist, S., 2009. Social Learning Processes in Swiss Soil Protection—The 'From Farmer - To Farmer' Project. Hum. Ecol. 37, 475-489, https://doi.org/10.1007/s10745-009-9262-1.

Schut, M., Rodenburg, J., Klerkx, L., van Ast, A., Bastiaans, L., 2014. Systems approaches to innovation in crop protection. A systematic literature review. Crop Protection 56, International Journal of environmental studies98-108, https://doi.org/10.1016/j.cropro.2013.11.017.

Sebillotte, M., 1990. Systèmes de culture, un concept opératoire pour les agronomes, Les systèmes de culture, INRA ed, Paris, pp. 103-117.

Shrestha, A., Clements, D.R., 2003. Emerging Trends in Cropping Systems Research. J. Crop Prod. 8, 1-13, https://doi.org/10.1300/J144v08n01_01.

Sutherland, L.-A., Burton, R.J.F., Ingram, J., Blackstock, K., Slee, B., Gotts, N., 2012. Triggering change: Towards a conceptualisation of major change processes in farm decision-making. Journal of Environmental Management 104, 142-151, https://doi.org/10.1016/j.jenvman.2012.03.013.

Toderi, M., Powell, N., Seddaiu, G., Roggero, P.P., Gibbon, D., 2007. Combining social learning with agro-ecological research practice for more effective management of nitrate pollution. Environ. Sci. Policy 10, 551-563, https://doi.org/10.1016/j.envsci.2007.02.006.

Toffolini, Q., Jeuffroy, M.-H., Mischler, P., Pernel, J., Prost, L., 2017. Farmers' use of fundamental knowledge to re-design their cropping systems: situated contextualisation processes. NJAS - Wagen. J. Life. Sci. 80, 37-47, https://doi.org/10.1016/j.njas.2016.11.004.

Wigboldus, S., Klerkx, L., Leeuwis, C., Schut, M., Muilerman, S., Jochemsen, H., 2016. Systemic perspectives on scaling agricultural innovations. A review. Agron. Sustain. Dev. 36, 46, https://doi.org/10.1007/s13593-016-0380-z.