Marie Dupré [a*], Thierry Michels[a], Pierre-Yves Le Gal[b]

[a] (1) CIRAD, UPR HORTSYS, 97455 Saint-Pierre Cedex (La Réunion), France

(2) HORTSYS, Univ Montpellier, CIRAD, Montpellier, France

thierry.michels@cirad.fr

* Corresponding author: mariedupre92@gmail.com

[b] (1) CIRAD, UMR Innovation, F-34398 Montpellier, France

(2) Innovation, Univ Montpellier, CIRAD, INRA, Institut Agro, Montpellier, France

pierre-yves.le_gal@cirad.fr

Crop drivers in the shift from synthetic inputs to alternative practices in diversified farming systems

Abstract

Reducing the use of synthetic inputs by shifting to alternative practices is becoming a growing priority in the agricultural sector. This study aims to understand how farmers manage this shift on diversified horticultural farms. The implementation of alternative practices at the crop level was analyzed on 28 farms on La Réunion Island (France). The surveys conducted combined interviews with farmers and the use of a dedicated indicator. Implementation of alternative practices depends on (i) the specificities of each production case (PC) defined as the combination of a crop with its biological features, a production mode and an economic environment (available technical support and market specifications), and (ii) links between PC within a farm. Five clusters of PC were identified based on their specificities. Links between PC take the form of competition over farm resources or, conversely, exchanges of biomass, inputs, equipment and skills acquired on each PC. These results provide an analytical framework to help advisors better support the diversity of farm involvement in shifting from synthetic inputs to alternative practices.

Key words: crop management; production case; farm level; horticulture; Réunion Island.

1. Introduction

The growing use of synthetic inputs after the Second World War significantly contributed to increased agricultural productivity in both developed and developing countries. However, after several decades of intensive use, these inputs have been found to have negative effects on the natural environment and human health, raising questions regarding the sustainability of these production systems (Tilman, 1998). Alternative systems have been proposed by some researchers, farmers and consumer movements, such as agroecology based on natural resources, biological processes and agrobiodiversity within farms and territories (Gliessman, 2015; Nicholls et al., 2017). Although politicians and citizens are increasingly sensitive to the damage caused by conventional agriculture, only a minority of farmers have adopted alternative practices up to now (Geiger et al., 2010; Nave et al., 2013).

Numerous studies have sought to understand what drive farmers to adopt certain alternative practices to synthetic inputs such as conservation agriculture (Knowler and Bradshaw, 2007) and cover crops (Roesch-Mcnally et al., 2017). These studies have shown that adoption is affected by diverse drivers related to the characteristics of the farm, farmer, and farming practices studied (Pissonnier et al., 2016). However, these studies, which focused on one type of practice, do not consider all of the decisions that a farmer must make at the level of his or her farm and their underlying rationales. Other studies, which have focused on all of the new practices adopted by farmers, have confirmed that multiple, interacting drivers influence changes in practices, including climate, economic, technological, social and political drivers (Ouédraogo et al., 2017; Probst et al., 2012; Padel et al., 2019). Hill and MacRae (1996) have proposed the three-step ESR framework to analyze these change processes, i.e., (i) Efficiency: improvement in the use of synthetic inputs; (ii) Substitution: when synthetic inputs are replaced by certified organic inputs that come from outside the farm, and (iii) Redesign: where the farmer rethinks the entire production system to use beneficial interactions between agroecosystem components, relying on resources from within the farm. Although the "E" step represents a way to reduce the use of synthetic inputs that farmers can justify based on economic reasons, the implementation of alternative practices starts with the "S" step, and the "R" step assumes a strategic change in the farmer's orientations (Chantre and Cardona, 2014).

These previous works focused on fairly specialized farms, where interactions between crop and eventually animal productions are minimized. In diversified systems, the implementation of alternative practices may be more complex, but the process also may be facilitated as farmers make changes based on the characteristics of the different productions on their farms (Coquil et al., 2013). Although diversified systems are widespread around the world, there is a lack of information on how farmers implement alternative practices in such contexts.

This study is based on 28 comprehensive surveys conducted on diversified horticulture farms on the island of La Réunion (France). Farming systems are highly diverse on the island due to a large range of soil and climatic conditions, a wide diversity of farm resources (land, workforce), and the co-existence in the horticultural sector of formal marketing channels based on supermarkets and a tradition of informal short chains. In the 1980s, synthetic inputs were adopted on a massive scale in line with the European agricultural policy (CAP) at the time. However, CAP is currently encouraging farmers to reduce these synthetic inputs through bans on active substances and subsidies to adopt alternative agroecological practices. In this context, the study aims to understand the role of crop drivers in farmers' implementation of alternative practices to synthetic inputs involving weed control, fertilization and crop protection. After presenting the survey and analysis protocol, we show how the characteristics of each crop and the links between crops within a farm affect the implementation of alternative practices. These results are then discussed based on other cases and on their operational contributions to agroecological transition.

2. Methods

2.1. Context of the study and sample

La Réunion is a small French island located in the Indian Ocean (2512 km²; 21° 06′ 52″ South, 55° 31′ 57″ East) and integrated into the European Union. Diverse crops are cultivated including sugar cane, forage, fruits and vegetables (respectively 58, 26, 7 and 6% of the utilized agricultural area), and secondary crops such as spices. This diversity of output is related to the island's varied topography (altitudes of 0 to 3000 m), soils (27 types) and climate (from 500 mm/year and 24°C on average on the west coast to 8000 mm/year and 12°C at altitudes of 2000 m). Farms are small with an average size of 6 ha. Farms which do not grow sugar cane (61% of the total) are highly diversified.

The explanatory objective of this study, and its focus on farmers' decision-making processes, led to a research methodology based on case studies. Such a methodology allows an understanding of the processes studied by combining an in-depth investigation of each case and both comparative and inductive analyses of the information collected individually (Eisenhardt and Graebner, 2007). The value of this method depends on the diversity of the cases studied relative to the issue addressed in order to enrich the explanatory capacity of the research process. In that respect a limited number of farms (28) were studied in detail, taking into account their individual contexts. The choice of these farms aimed to cover a wide range of situations rather than a statistically representative sample of the island's farming population. The selection was based on three criteria identified by past studies as being potentially related to the adoption of alternative practices (Bellon et al., 2001; Pissonnier et al., 2016) and for which data could be obtained easily. The criteria were: the main marketing channel as a proxy for consumer demand regarding the characteristics of agricultural products and, consequently, the kind of practices requested to produce them; organic certification as a proxy for strategic choices made by farmers that lead to the implementation of alternative practices; and farm size as a proxy for farm resources, especially labor and cash, which may hinder such implementation. The farms all cultivate citrus because the same sample was used to understand the diversity of agroecological practices in citrus orchards (Dupré et al., 2017). Due to the purpose of this study, four farms cultivating only citrus were removed from the original 32-farm sample, which ultimately included 6 holdings certified as organic farms and 22 non-certified farms (Table 1). Production was sold through cooperatives, direct sales, small resellers or directly to processors. Farmers' contact information was obtained from different sources: agricultural technicians, cooperatives, agricultural input dealers, certification bodies and consumer associations.

2.2. Surveys

The farmers were surveyed between December 2015 and September 2016. The surveys consisted of one or two semi-structured interviews lasting one to three hours with the farm head, combined with a visit of the farm. The discussion was organized in order to:

(i) identify the production cases implemented by each farm, a production case (PC) being defined as a combination of a crop, its production mode (e.g., field *vs* greenhouse; organic *vs* conventional) and its economic environment, which was defined as the marketing channel and technical support characterized by the absence or presence of contact between the farmer and an adviser for a given case;

(ii) describe the farming practices used on each PC that had been implemented on the farm for at least two years. Three sets of practices, common to all of the crops produced and which could involve the use of synthetic inputs, were investigated more precisely: crop protection, fertilization and weed control.

(iii) characterize the reasons behind farmers' choices in relation to both the specificities of each PC and the interactions between the various PCs within a given farm.

Based on this dataset, 93 PC were identified on the 28 farms surveyed. They included six perennial fruit crops, six semi-perennial crops (sugar cane, christophine and fruits) and seven short cycle crops (Table 1). Each crop has specific biological features that may affect the farmer's choices of farming practices regarding crop protection, fertilization and weed control (Table 2).

Table 1. Farm characteristics and number of production cases (PC) per crop and per farm.

Farm code	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	**Total**
Zone[1]	4	3	7	2	7	1	6	5	6	5	7	7	5	6	7	7	7	5	7	7	7	8	8	7	5	6	8	6	
Farm area (ha)[2]	3	3.5	1	1.5	6.5	12	3.5	8.8	4	5	6.5	2.4	5	7.9	8	12	6	7	1	22	5	5	4	1	2.5	14	9	15	
Certification[3]			OF	OF			OF					OF							OF								OF		
Markets[4]	1	2	3	3	1;3;4	2	3	1	1;4	1	1	3	1	2	3	1	2	1	2	2;4	2	2;3	3	2	1	2	2	2;4	
Perennial fruit crops																													
Avocado			1	1																									2
Citrus	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	28
Lychee		1							1	1																			3
Mango		1				1		1					1				1												5
Peach				1		1			1										1			1	1						6
Persimmon											1																		1
Semi perennial crops																													
Banana				1										1									1				1		4
Christophine																						1					1		2
Papaya						1		1		1			1	1															5
Passion fruit						1									1		2[5]			2[5]						1		1	8
Pineapple														1						1		1	1			1			5
Sugarcane																		1										1	2
Short cycle crops																													
Chilli																								1		1			2
Ginger					1							1		1		1													4
Maize																						1							1
Pumpkin										1																			1
Strawberry	1														1														2
Thyme																		1							1				2
Tomato							1	1					2[5]				1			2[5]	2[5]						1		10
Total PC	2	3	2	4	2	5	2	4	3	4	2	2	5	5	3	2	5	3	2	6	3	5	4	2	2	4	4	3	**93**
Livestock												1			1				1				1					1	

[1] 1: South-west > 600m; 2: South-west 300-600m; 3: South > 500m; 4: West > 600m; 5: West < 600m; 6: South 300-500m; 7: South <300m; 8: East (mountains). Each zone is characterized by specific temperatures and rainfall which potentially affect weed competition and pressure of pests and diseases, and so the choice of farming practices.

[2] As a proxy of the labor and cash resources available in the farm for implementing alternative practices

[3] OF: Organic Farming. The six farms implement alternative practices by following OF specifications on all their crops.

[4] 1: Local retailers; 2: Cooperatives; 3: Direct selling; 4: Juice industry. Each market has specific requests regarding the products marketed, which impact farming practices.

[5] Open field crop for one case, greenhouse for the other one.

Table 2. Biological features of the 19 crops studied. High sensitivity or needs are indicated with "+" and low sensitivity or needs with "-". Sensitivity to fruit and vegetable flies (the main pests in the study area) and sensitivity to weed competition are based on expert knowledge. Nutrient needs are based on data from Chambers of Agriculture [Ferti-RUN software (http://www.mvad-reunion.org/spip.php?article107)].

	Sensitivity to (fruit and vegetable) flies	Nutrient needs	Sensitivity to weed competition
Perennial crops			
Avocado	+	+	-
Citrus	+	+	-
Lychee	-	-	-
Mango	+	-	-
Peach	+	+	-
Persimmon	+	-	-
Semi perennial crops			
Banana	-	+	-
Christophine	+	+	-
Papaya	-	+	-
Passion fruit	-	+	+
Pineapple	-	+	+
Sugarcane	-	+	-
Short cycle crops			
Chilli	+	+	+
Ginger	-	+	+
Maize	-	+	+
Pumpkin	+	-	+
Strawberry	+	+	+
Thyme	-	-	+
Tomato	+	+	+

2.3. Choice of an ecologization indicator: the Technical Score

The ecologization of practices comprises both the reduction of synthetic inputs and the implementation of alternative practices to these inputs. The Technical Score (TS) was created to easily assess this dual process (Dupré et al., 2017). In this study, the only synthetic inputs considered are synthetic pesticides and fertilizers. All the other practices are considered as alternative. Some practices implemented by the farmers at the time of the survey were regrouped by production mode to avoid going into the details of each input. For example, treatments were divided into two modes: synthetic or certified organic.

Calculated per PC, the TS enables all of the crops to be compared. It cannot, however, be applied directly to animal production because the three sets of practices considered, namely crop protection, fertilization and weed control, are specific to crop production. Animal production, present on 18% of the farms surveyed, was therefore excluded from the analysis of the TS.

The TS only considers the nature of the input used (synthetic or not) and not the quantity (Eq. 1). It consequently is possible to conduct the analysis without quantitative data on the inputs. This degree of detail is thus adapted to the study of practice implementation that may not be accompanied by written records. For each set of practices (crop protection, fertilization and weed control), the score can be -1, 0 or 1. The accumulation of alternative practices in the same group is not counted. As a result, the sum of the scores of each group makes the TS vary from -3 (management based on synthetic inputs alone) to +3 (management with no synthetic inputs). Values between -2 and +2 correspond to many combinations of synthetic inputs and alternative practices.

$$TS^j = \sum_{i=1}^{3}(A_i^j - C_i^j) \qquad \text{(Eq. 1)}$$

TS^j = Technical Score of crop j

i = index of group of practices (Protection; Fertilization; Weed control)

A_i = 1 if at least one alternative technique is implemented for group i; 0 otherwise

C_i = 1 if at least one synthetic input is used for group i; 0 otherwise

2.4. Analysis of the implementation of alternative practices

The TS per PC was calculated based on the current practices for the 93 PCs identified on the 28 farms. First, the TS of PCs on the same farm were compared with each other. In order to then compare farms, a TS per farm was calculated by summing the TS of each PC on the farm divided by the number of PCs considered. Relationships between the biological, technical and economic characteristics of PCs and the implementation or non-implementation of alternative practices were statistically tested for all occurrences reported at least once by a farmer. The Fisher test was used for occurrences that were poorly represented (number <5) or had unbalanced marginal sums in the contingency table; the Chi-2 test was used for the other cases.

A multivariate statistical analysis combining a Multiple Correspondence Analysis (MCA) with an Ascending Hierarchical Classification (AHC) (Cortez-Arriola et al., 2015; Kuivanen et al., 2016) was then performed to regroup the 93 PCs into homogeneous clusters with regard to their TS values divided into three classes: Low (<-1), Intermediate (-1 to 1) and High (>1). The analyses were performed on R (version 3.3.2) with the FactoMineR package (version 1.34) (Josse, 2008).

Based on the 28 farmers' interviews, this PC-focused analysis was then complemented on each farm by the identification of links between PCs leading to a shift of practices towards the reduction of synthetic inputs. Indeed, it was assumed that a change in the practices used for a PC could stimulate or hinder changes in the other PCs cultivated on the farm and impact their TS in these diversified systems. The 45 qualitative occurrences collected from farmers' answers were then regrouped into three processes that were formalized qualitatively by comparing the farmers' decision-making processes driving them.

3. Results

3.1. A diversity of alternative practice implementation

The current systems were studied with regard to the implementation of alternative practices to synthetic inputs and the diversity of TS levels at the PC and farm scales. Twenty alternative practices were observed on the farms surveyed (Fig. 1). The most frequently implemented were mowing, weeding with tillage, spot application of herbicides, use of manure or compost, biopesticides and chemical traps. The rarest were agro-pastoralism, insect-proof nets and sprinkler irrigation for the control of certain pests. Plastic mulching, restitution of crop residues, release of natural enemies, cover crops and agro-pastoralism remained specific to certain PCs. The fifteen other practices were most often partially implemented by farms, but sometimes were implemented on all of the PCs. The mean TS of the 93 PCs was 0.31. While positive, this average is far from the maximum score (+3), and shows that the reduction of synthetic inputs was ongoing for most of the PCs identified.

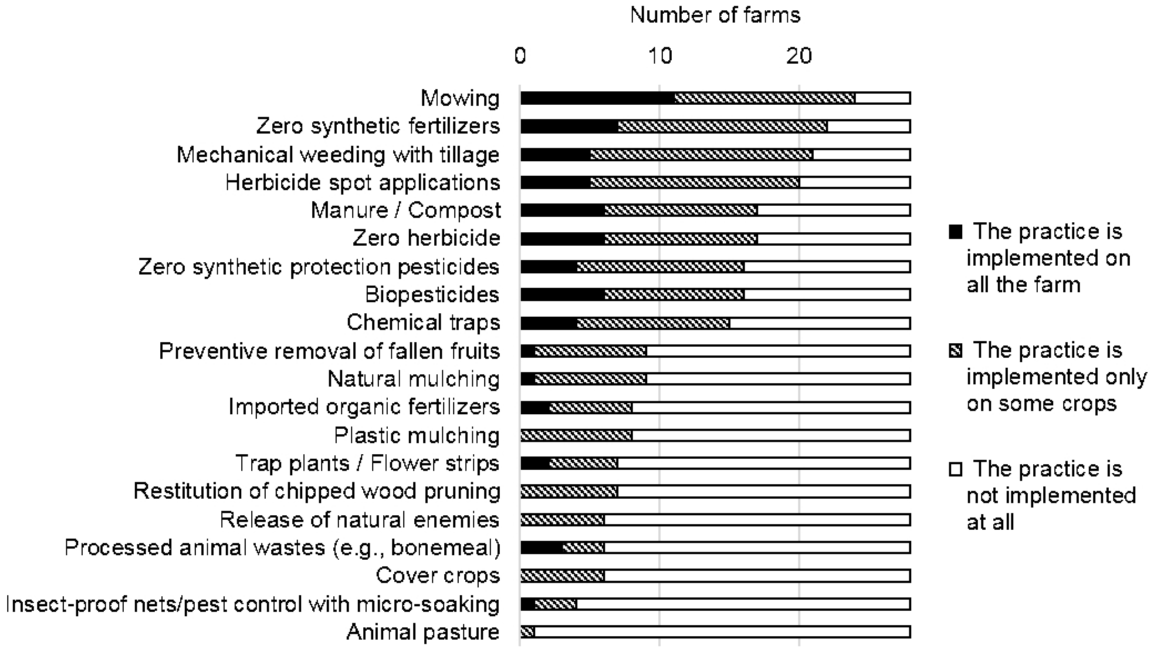

Figure 1. Extent of implementation of 20 agroecological practices on the 28 farms surveyed.

This result was confirmed at the farm scale, where the TS per farm ranged from -2.25 to +3, showing that the farmers were at different levels of change in their practices. Only 29% of the farms surveyed showed a same TS for all of their PCs. These eight farms covered a large range of TS per farm (from -1 to 3) and cultivated between two and four PCs. The next two sections explain this diversity by investigating the effects on the implementation of these alternative practices of (i) distinctive PC characteristics and (ii) PC links within the diversified farms.

3.2. Effects of the characteristics of production cases on the implementation of alternative practices

First, the links between the diversity of TS levels and PC characteristics as defined above were explored. The relationships between the biological characteristics of the crops and practices are statistically significant except for the use of herbicide and synthetic fertilizers (Table 3).

Obviously crops that are not sensitive to fruit and vegetable flies do not need chemical traps or preventive actions involving the destruction of fruits damaged by flies. A high sensitivity to competition from weeds leads to a high implementation of mulching and a low implementation of a permanent cover-crop to mow. Natural mulching is mainly used for long cycle crops while plastic mulch, which degrades in a few months and has to be removed, is used on short cycle crops.

The PCs' specific economic contexts also impact the implementation of alternative practices when technical support is available. For example, the release of natural enemies is closely linked to the existence of strong technical support promoting this type of practice on certain crops (strawberries) and not on others (citrus fruits). The specific demands of buyers also influence farmers' choices of practices. Sales through channels with low visual quality requirements (direct sales or processing) lead to the absence of protective pesticides, whether or not organic certified. However, by itself organic certification does not lead to a greater use of imported organic fertilizer or biopesticides, which are used in a similar proportion on non-certified PCs.

Table 3. Relationship between biological and economic characteristics of the 93 production cases (PC) and implementation of alternative practices.

PC features			Practices		Test p-value
Biological			Traps/prophylaxis		
			Yes	No	
	Sensitivity to fruit flies	Low	7	27	4.00e-02[a]*
		High	26	33	
			Synthetic fertilizers		
			No	Yes	
	Nutrient needs	Low	5	7	3.51e-01[b]
		High	48	33	
			Mulching		
			Yes	No	
	Cycle duration	Short	15	7	5.05e-05[a]*
		Medium	13	13	
		Long	7	38	
			Mulching		
			Yes	No	
	Sensitivity to weed competition	Low	12	46	3.77e-05[a]*
		High	23	12	
			Mowing		
			Yes	No	
		Low	46	12	3.01e-04[a]*
		High	14	21	
			Herbicide		
			No	Yes	
		Low	24	34	8.53e-01[a]
		High	13	22	
Economic context	Certification		Imported organic fertilizers		
			Yes	No	
		OF	5	9	1.52e-01[b]
		None	14	65	
			Biopesticides		
			Yes	No	
		OF	5	9	5.69e-01[b]
		None	36	43	
			Release of natural enemies		
			Yes	No	
	Technical support	Low	3	77	1.09e-03[b]*
		High	5	8	
			Organic or synthetic protection treatments		
			No	Yes	
	Marketing constraints on visual	Low	13	11	3.11e-04[a]*

quality	High	10	59

[a] Chi-2 [b] Fisher *P = 0.05

Based on these correlations and a multivariate analysis, five clusters of PCs were constituted which provide a synthetic view of the links between the PC features and the implementation of alternative practices evaluated by the mean TS per cluster (Table 4; Appendix A). The highest mean TS (C1 cluster) is achieved by PCs for which (i) effective alternative practices exist which are inexpensive and (ii) do not require specific technical support, combined (iii) with marketing channels accepting low visual quality (direct sales, processing or sales under the AB label), which enables limited use of protective treatments. It includes mainly perennial crops that are either not very susceptible to competition from weeds, which favors the implementation of mechanical mowing, or highly susceptible to fruit flies, leading to the implementation of the preventive removal of fallen fruit and chemical traps.

With a much lower but still positive TS, the C2 cluster groups annual crops (strawberry, tomato) and semi-perennial crops (passion fruit, christophine) mainly grown under shelters and accompanied by strong technical support recommending the release of natural enemies and the use of plastic or natural mulching rather than herbicide. However, the reliance on sales channels with highly demanding visual quality requirements limits the margins of reduction of the protective treatments.

The C3 cluster mainly contains perennial crops identical to C1, with a similar implementation of mowing, chemical traps and removal of fallen fruit. But the productions are marketed in sales channels with very demanding visual quality requirements which limit the reduction of the protective treatments and leads to a mean TS close to the C2 one. The C4 cluster includes annual or semi-perennial crops for which alternative practices are currently more risky or expensive than synthetic inputs, combined with the absence of specific technical support and very demanding sales channels with regard to visual quality. These combinations lead to a limited implementation of alternative practices and a mean TS similar to C3.

The last cluster (C5) has a very negative mean TS, reflecting a heavy reliance on synthetic inputs. It mainly contains semi-perennial crops identical to C4, but the farmers cultivating them are facing constraints with regard to labor or input availability which hinder implementation of mowing and organic fertilization. The reduction of synthetic inputs is also limited by the requirements of the sales channels in terms of yield (sugar cane) or visual quality (pineapple and passion fruit for export).

Of the 19 crops identified in the sample, 10 belong to only one cluster, showing that biological features alone cannot explain the farmers' choices in terms of alternative practices. The crop environment in terms of technical support and marketing channels explains why the remaining nine crops are distributed between two, and more rarely three clusters.

Table 4. Distribution of the 93 production cases between the five clusters according to their crops

Cluster	C1	C2	C3	C4	C5	Total
TS mean	1.62	0.33	0.17	0.10	-1.75	0.33
Perennial crops						
Avocado	2					2
Citrus	11		16		1	28
Lychee				3		3
Mango	1		4			5
Peach	4		2			6
Persimmon			1			1
Semi-perennial crops						
Banana	1			3		4
Christophine		2				2
Papaya				5		5
Passion fruit		3		4	1	8
Pineapple				2	3	5
Sugarcane					2	2

Short-cycle crops						
Chilli				1	1	2
Ginger	1			3		4
Maize				1		1
Pumpkin				1		1
Strawberry		2				2
Thyme				2		2
Tomato	1	5		4		10
Total	21	12	23	29	8	93

At the farm level, only seven farms have all of their PCs in one cluster, either because they are organic (C1), or at the other extreme because their labor availability limits the implementation of alternative practices (C5). For the 21 other farms, up to 3 clusters can be observed per farm regardless of their number of PCs (Fig. 2). This result demonstrates that the reduction of synthetic inputs is not a homogenous process on these diversified farms. This is due to the specificity of PCs, as shown in this section, but also to the variety of links between PCs within a farm, which will be shown in the following section.

Figure 2. Distribution of the 28 farms according to their number of production cases and their number of clusters

3.3. Effects of links between production cases within farms on the implementation of alternative practices

The way a farmer chooses practices on one PC may depend on the other PCs cultivated within the farm. Three main types of links were identified between PCs: (i) ripple effect when the implementation of an alternative practice on one crop triggers its implementation on another crop; (ii) flow of goods between PCs that enables the implementation of an alternative practice; (iii) conditionality when the implementation of an alternative practice on one PC is conditional on its non-implementation on other PCs, particularly in cases where limited labor or cash flows are constraints.

Observed 20 times, the ripple effect process covers two types of situations: (i) the farmer, having tested a new practice on one PC with satisfactory results, then implements the practice on another. This thus consists of a dissemination of skills acquired on an initial PC to other PCs on the farm; (ii) the farmer introduces alternative goods which are then pooled for use over several PCs to simplify management and reduce their costs per unit produced. The dissemination of skills is observed particularly in farms with at least one PC that has strong technical support (C2 cluster) which is the "gateway" to innovation. The practices disseminated are chemical traps, organic fertilization, natural mulching and mowing. For example, farmer F1 receives considerable technical support for his strawberry PC. In 2010, he is advised to stop using herbicides and to leave a permanent, mowed grass cover between rows. Satisfied with the effects of this cover on reducing mite pressure and the number of acaricide treatments, he began practicing mowing on citrus fruits in 2012 without having received technical advice for this PC.

The pooling of alternative goods is observed between all clusters except for the C5 cluster, which has a low TS. Pooled inputs are organic fertilizers, chemical traps and biopesticides. Pooled equipment consists of rotary cutters for mowing and grinding branches to recycle crop residues and natural mulching. For example, farmer F9 only cultivates perennial fruits which are all sold through the same sales channel. In 2014, he replaced synthetic fertilizers with an organic fertilizer (feather meal and poultry blood) on all of his PCs so that he only had to buy and transport one type of fertilizer. Farmer F7 bought a piece of equipment he could use both for shredding citrus branches after pruning and for mulching with Ramial Chipped Wood on tomato.

The existence of flows of goods between productions was observed 13 times. Farmers put them in place to reduce their purchases of external inputs and manage their 'waste', i.e., crop residues or livestock manure. These links were observed on the farms with mean TSs that were slightly positive to high. Seven types of goods are involved in these flows: seeds of flower strips and natural enemies that are initially purchased, multiplied on one PC, and then transferred to other PCs; natural mulch produced on the farm and used on some PCs; the residues of soil-less PCs and their substrate that are transferred to fertilize soil-grown PCs; manure/slurry from animals on the farm that is transferred to fertilize PCs; and finally hay produced from spontaneous ground cover.

Observed 12 times, conditionality in the allocation of farm resources is linked to two constraints which are sometimes combined: (i) a limited labor force which forces the farmer to choose less time-consuming practices for certain PCs to prioritize the management of other PCs; (ii) a limited cash flow which forces the farmer to concentrate investments in goods on certain PCs to the detriment of others. PCs that are major contributors to farm income or have higher economic margins are considered to be the "priority" for labor and cash flow.

These conditionality mechanisms lead to the only partial implementation of alternative practices that are more time-consuming or expensive: organic fertilization compared to synthetic fertilizers, mowing with some mechanization compared to herbicides, natural cane-based mulching which is expensive (€1,600/ha to renew once a year), the preventive removal of fallen fruit and flower strips that require additional time. This partial implementation negatively affects the TS per farm, as shown by the 5 farms which implement only this kind of link between PCs (Table 5). For example, farmer F22 has practiced the preventive removal of fallen fruit for citrus since 2006. This takes time during the harvest, which is already a peak period of work. Despite the effectiveness of the practice, his labor force constraints led him to decide not to implement it on christophine because it is a secondary PC on the farm. Farmer F1 has been using organic fertilizers on his strawberries since 2006, but not on his citrus trees because he considers that only strawberries allow him to generate a profit while using this expensive fertilizer.

This crop-link process concerns the majority of the farms surveyed. Only eight farms cultivating from 2 to 5 PCs do not show any link between PCs (Table 5), six out of them showing null or negative TS. For the 20 other farms, the process concerns up to five links on the farm. The group of 10 farms that only have links stimulating change of practices have the highest mean TS per farm, while the combination of both stimulating and hindering links leads to a slightly positive mean TS. Although each group shows some TS diversity, this trend illustrates the contribution of existing links on the implementation of alternative practices.

Table 5. Distribution of farms and TS per farm according to the kind of links between production cases

	No link	Trigger + Flow of goods	Conditionality	Both
Number of farms	8	10	5	5
TS per farm				
Mean	-0.42	1.15	-0.24	0.35
Mini	-2.25	-0.20	-1.33	-1.50
Max	1.50	3.00	1.00	1.50

4. Discussion

4.1. A combination of crop drivers

Although based on a small sample of diversified farms, this study has shown that the reduction of synthetic inputs through the implementation of alternative practices combines various drivers linked to the crop level, as previously highlighted by Brodt et al. (2007) in a study conducted in California among almond and wine grape growers. These drivers can be classified into four categories pertaining to: (i) the biological characteristics of crops, integrated into the farm's soil-climate context, including sensitivity to pests, (ii) the crops' specific environment regarding the availability of inputs, sales channels and the type of technical advice provided, (iii) the existence and the specific characteristics of the alternative practices proposed, such as their cost, workload and the technical complexity of their implementation, (iv) some farm's specific characteristics, particularly its labor and capital resources. The various combinations of these different categories of drivers within a farm explains why a farmer may decide to change his practices on one crop, for example one that is not very sensitive to pests or sold directly to consumers, and not on another crop whose specifications seem too restrictive to do so.

This study also emphasizes the impact on the change of links between agricultural activities within the farm. The dissemination of new skills, required for the technical mastery of alternative practices, is a key driver in stimulating processes of change (Merot and Wery, 2017; Toffolini et al., 2015). Similarly, the pooling of inputs and equipment to reduce costs, or to the contrary, the concentration of these on the most lucrative activity, enables certain economic barriers to be overcome. Herrero et al. (2010) also show that biomass exchanges, especially on mixed crop-livestock farms, are particularly favorable to the implementation of alternative fertilization practices. Changes in the farmer's environment, such as the banning of certain products, incentives through technical advice and public support, as well as new consumer demands, are also important triggers for a reduced use of synthetic inputs (Chantre and Cardona, 2014).

Although generic, this crop-based framework of analysis is expressed differently according to the context in which the farm evolves (Grover and Gruver, 2017). The isolation of La Réunion as an island complicates access to alternative inputs such as organic fertilizers and pest control products, both in terms of physical availability and higher costs. Promoting the reduction of synthetic inputs in a territory thus leads to identifying its specific regional features (Fairweather and Campbell, 2003).

4.2. From Substitution to Redesign

By distinguishing efficiency, substitution and redesign as pathways of change towards more sustainable farming systems, Hill and MacRae (1996) opened a debate about the way to reduce synthetic inputs that remains lively and timely. Redesign advocates argue that substitution has the potential, through a "lock-in" effect (Wagner et al., 2016), to block farmers at a low level of change of practices that is insufficient to meet current social and environmental challenges (Rosset and Altieri, 1997). But some actors, including farmers’ unions, highlight the economic, organizational and technical difficulties posed by redesign on farms. These difficulties force farmers to take risks while facing markets, and therefore consumers, who may not be "ready" to accept agricultural products with visual defects that are sold at higher prices.

By focusing on the crop level, our study does not assess the capacity or willingness of farmers to redesign their systems at farm scale following the principles of agroecology. This would involve not only reducing their use of synthetic inputs at field scale, but also implementing agroecological principles as intercrops, crop rotations, agroforestry or diversified landscape mosaics (Altieri, 1999; Jackson et al., 2007; Martin-Guay et al., 2018; Rosset and Altieri, 1997). However, our crop scale study nonetheless highlighted that farmers follow a diversity of pathways: from individual changes of practices on selected crops to the simultaneous implementation of several alternative practices on all of the farm crops. Progressive pathways are consistent with the anti-risk strategies that most farmers are keen to implement (Dupré et al., 2017; Ridier et al., 2013) Indeed, they experiment and learn about crops managed under a redesign strategy while securing their income on crops where they use substitution. In doing so, they adapt to markets by redesigning crops with less demanding niche markets and by using substitution on crops whose conventional markets are very demanding.

4.3. Supporting farmers towards the redesign of agroecological farming systems

Given the diversity of individual situations, the approach used here, one based on the TS indicator, makes it possible to diagnose each farm and compare farms with each other while revealing how farmers reduce the use of synthetic inputs. This step is important to consider with farmers possible changes in their production systems (Le Gal et al., 2011). Through its flexibility, the TS indicator makes it possible to take into account all types of practices, conventional and agroecological, in plant production. Its adaptation to animal production seems conceivable, integrating the practices of feeding, sanitary management and effluent management, according to the agroecological principles described by Dumont et al. (2013). The TS could then provide a tool to assess the ecologization of mixed crop-livestock farms. However, this indicator, which can be used for static and dynamic studies, remains purely descriptive. It should be coupled with approaches such as Life Cycle Assessment (Hellweg and Milà I Canals, 2014) to go further in assessing the effects of changes in practices on the environmental, economic and social performance of farms.

These tools could be integrated into on-farm extension services which are still largely lacking in contexts such as La Réunion, where technical support remains very sector specific (Rebuffel et al., 2015). This support to small diversified farms could be based on discussion groups and experiments between farmers (Warner, 2006) with contexts of action and convergent objectives for greater effectiveness (Oerlemans and Assouline, 2004). The analytical framework formalized in this study provides a basis for forming such groups.

5. Conclusion

Following the public health, food and environment challenges posed by a production-focused agricultural model, agroecological transition is a concept that has moved from the scientific sphere to political and social spheres. Through their farming practices, farmers are at the forefront of the debate, yet the reasoning behind their choices are not always clearly laid out. This study focusing on the crop level provides new insights by showing that on diverse farms, biological and economic specificities of crops and links between crops at the farm level can explain how and why farmers implement alternative practices to the use of synthetic inputs.

These results highlight the real efforts made by farmers to reduce their use of synthetic inputs, but also the gap between the entrenched positions encountered far too often in political and social debates, and the reality they experienced. Furthermore, barriers to change also depend heavily on actors outside the agrifood sector, especially consumers, because their quality and price requirements may be incompatible with farmers' technical and economic capacities of change. The study and accompaniment of agroecological transition must therefore go beyond these ideological debates to propose to farmers trajectories of change which are adapted to their individual context and involve all of society in this transition.

Acknowledgments

We are very grateful to the farmers and all of the stakeholders we met for the valuable data they provided and the rich discussions we shared with them. We thank Grace Delobel for editing the paper in English, and the two anonymous reviewers whom comments helped us to improve the article. This work was supported by the French Agricultural Research Centre for International Development (CIRAD) and the European Agricultural Fund for Rural Development (EAFRD).

References

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agric., Ecosyst. Environ. 74, 19-31. https://doi.org/10.1016/S0167-8809(99)00028-6

Bellon, S., Lescourret, F., Calmet, J.-P., 2001. Characterisation of apple orchard management systems in a French Mediterranean Vulnerable Zone. Agronomie. 21, 203–213.https://doi.org/10.1051/agro:2001118

Brodt, S., Klonsky, K., Tourte, L., Duncan, R., Hendricks, L., Ohmart, C., Verdegaal, P., 2007. Influence of farm management style on adoption of biologically integrated farming practices in California. Renew. Agric. Food Syst. 19, 237-247.https://doi.org/10.1079/rafs200488

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. Sustain. Food Syst. 38, 573-602.https://doi.org/10.1080/21683565.2013.876483

Coquil, X., Béguin, P., Dedieu, B., 2013. Transition to self-sufficient mixed crop–dairy farming systems. Renew. Agric. Food Syst. 29, 195-205.https://doi.org/10.1017/S1742170513000458

Cortez-Arriola, J., Rossing, W.A.H., Massiotti, R.D.A., Scholberg, J.M.S., Groot, J.C.J., Tittonell, P., 2015. Leverages for on-farm innovation from farm typologies? An illustration for family-based dairy farms in north-west Michoacán, Mexico. Agric. Syst. 135, 66-76.http://dx.doi.org/10.1016/j.agsy.2014.12.005

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., Tichit, M., 2013. Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal. 7, 1028-1043.https://doi.org/10.1017/S1751731112002418
Dupré, M., Michels, T., Le Gal, P.-Y., 2017. Diverse dynamics in agroecological transitions on fruit tree farms. Eur. J. Agron. 90, 23-33.https://doi.org/10.1016/j.eja.2017.07.002
Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: Opportunities and challenges. Acad. Manage. J. 50, 25-32.https://doi.org/10.5465/AMJ.2007.24160888
Fairweather, J.R., Campbell, H.R., 2003. Environmental beliefs and farm practices of New Zealand farmers Contrasting pathways to sustainability. Agr. Human Values. 20, 287-300.https://doi.org/10.1023/A:1026148613240
Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Oñate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11, 97-105.https://doi.org/10.1016/j.baae.2009.12.001
Gliessman, S.R., 2015. Agroecology: the ecology of sustainable food systems, C. press (Ed.)
Grover, S., Gruver, J., 2017. 'Slow to change': Farmers' perceptions of place-based barriers to sustainable agriculture. Renew. Agric. Food Syst. 32, 511-523.https://doi.org/10.1017/S1742170516000442
Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science. 344, 1109-1113.https://doi.org/10.1126/science.1248361
Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems. Science. 327, 822-825.https://doi.org/10.1126/science.1183725
Hill, S.B., MacRae, R.J., 1996. Conceptual Framework for the Transition from Conventional to Sustainable Agriculture. J. Sustainable Agric. 7, 81-87.https://doi.org/10.1300/J064v07n01_07
Jackson, L.E., Pascual, U., Hodgkin, T., 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. Agric. Ecosyst. Environ. 121, 196-210.https://doi.org/10.1016/j.agee.2006.12.017
Josse, J.H., F., 2008. FactoMineR: An R Package for Multivariate Analysis. J. Stats. Softw. 25, 1-18.https://doi.org/10.18637/jss.v025.i01
Knowler, D., Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food Policy. 32, 25-48.https://doi.org/10.1016/j.foodpol.2006.01.003
Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., Groot, J.C.J., 2016. Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: A case study from the Northern Region, Ghana. NJAS - Wageningen Journal of Life Sciences. 78, 153-166.https://doi.org/10.1016/j.njas.2016.04.003
Le Gal, P.-Y., Dugué, P., Faure, G., Novak, S., 2011. How does research address the design of innovative agricultural production systems at the farm level? A review. Agric. Syst. 104, 714-728.https://doi.org/10.1016/j.agsy.2011.07.007

Martin-Guay, M.-O., Paquette, A., Dupras, J., Rivest, D., 2018. The new Green Revolution: Sustainable intensification of agriculture by intercropping. Sci. Total Environ. 615, 767-772.https://doi.org/10.1016/j.scitotenv.2017.10.024

Merot, A., Wery, J., 2017. Converting to organic viticulture increases cropping system structure and management complexity. Agron. Sustain. Dev. 37, 19. https://doi.org/10.1007/s13593-017-0427-9

Nave, S., Jacquet, F., Jeuffroy, M.-H., 2013. Why wheat farmers could reduce chemical inputs: evidence from social, economic, and agronomic analysis. Agron. Sustain. Dev. 33, 795-807.https://doi.org/10.1007/s13593-013-0144-y

Nicholls, C., Altieri, M., Vazquez, L., 2017. Agroecological Principles for the Conversion of Farming Systems: Principles, Applications, and Making the Transition, in., pp. 1-18.https://doi.org/10.1142/9781786343062_0001

Oerlemans, N., Assouline, G., 2004. Enhancing farmers' networking strategies for sustainable development. A modified version of this paper was presented at the 15th ESEE Conference, August 2001, Wageningen, The Netherlands. Journal of Cleaner Production. 12, 469-478.https://doi.org/10.1016/S0959-6526(03)00105-7

Ouédraogo, M., Zougmoré, R., Moussa, A.S., Partey, S.T., Thornton, P.K., Kristjanson, P., Ndour, N.Y.B., Somé, L., Naab, J., Boureima, M., Diakité, L., Quiros, C., 2017. Markets and climate are driving rapid change in farming practices in Savannah West Africa. Regional Environmental Change. 17, 437-449.https://doi.org/10.1007/s10113-016-1029-9

Padel, S., Levidow, L., Pearce, B., 2019. UK farmers' transition pathways towards agroecological farm redesign: evaluating explanatory models. Agroecol. Sustain. Food Syst. online. https://doi.org/10.1080/21683565.2019.1631936

Pissonnier, S., Lavigne, C., Toubon, J.F., Le Gal, P.Y., 2016. Factors driving growers' selection and implementation of an apple crop protection strategy at the farm level. Crop Protect. 88, 109-117.https://doi.org/10.1016/j.cropro.2016.06.007

Probst, L., Adoukonou, A., Amankwah, A., Diarra, A., Vogl, C.R., Hauser, M., 2012. Understanding change at farm level to facilitate innovation towards sustainable plant protection: a case study at cabbage production sites in urban West Africa. Int. J. Agr. Sustain. 10, 40-60. https://doi.org/10.1080/14735903.2012.649589

Rebuffel, P., Lemoine, C., Faure, G., 2015. Le difficile accès au conseil pour les petites exploitations agricoles : le cas de Mayotte. Cah. Agric. 24, 269-276.https://doi.org/10.1684/agr.2015.0771

Ridier, A., Ben El Ghali, M., Nguyen, G., Kephaliacos, C., 2013. The role of risk aversion and labor constraints in the adoption of low input practices supported by the CAP green payments in cash crop farms. Revue d'Etudes en Agriculture et Environnement. 94, 195-219. https://doi.org/10.4074/S1966960713012034

Roesch-McNally, G.E., Basche, A.D., Arbuckle, J.G., Tyndall, J.C., Miguez, F.E., Bowman, T., Clay, R., 2017. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. Renew. Agric. Food Syst. 1-12.https://doi.org/10.1017/S1742170517000096

Rosset, P.M., Altieri, M.A., 1997. Agroecology versus input substitution: A fundamental contradiction of sustainable agriculture. Soc. Nat. Resour. 10, 283-295.https://doi.org/10.1080/08941929709381027

Tilman, D., 1998. The greening of the green revolution. Nature. 396, 211-212. https://doi.org/10.1038/24254

Toffolini, Q., Jeuffroy, M.-H., Prost, L., 2015. Indicators used by farmers to design agricultural systems: a survey. Agron. Sustain. Dev. 36, 5.https://doi.org/10.1007/s13593-015-0340-z

Wagner, C.H., Cox, M., Bazo Robles, J.L., 2016. Pesticide lock-in in small scale Peruvian agriculture. Ecol. Econ. 129, 72-81.http://dx.doi.org/10.1016/j.ecolecon.2016.05.013

Warner, K.D., 2006. Extending agroecology: Grower participation in partnerships is key to social learning. Renew. Agric. Food Syst. 21, 84-94.https://doi.org/10.1079/RAF2005131