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Model-based assessment of technological innovation in banana cropping systems contextualized by farm types in Guadeloupe

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ABSTRACT

Farmers are inundated with advertisements about many innovations that are supposed to increase their yields or reduce environmental impact. However, the benefit of these innovations depends on the farming context. Here we present the *ad hoc* adaptation of the crop model SIMBA and a method to evaluate 16 innovations in six types of farms previously selected through a typology of the banana farming systems in Guadeloupe. The innovations include regulation of pesticide use, rotations and fallows, intercropping, conditional application of pesticides, resistant cultivars, and integrated systems. Our results show that, for a given innovation, the yield and pesticide reduction vary widely with different farm types. We show that environmentally friendly innovations often cause a greater decrease in yield in more productive farm types. Nevertheless, despite an apparent trade-off between yield and pesticide use, some innovations address both production and environmental issues, e.g., rotation with fallows improved with cover crops, regular fallows, and rotations with pineapples for the most intensive farm types. Our modelling study confirms the importance of innovation-farm type interactions and the usefulness of models for assessing large numbers of technological innovations among a wide range of biophysical and technical contexts.

1. Introduction

Given the increasing societal demand for more eco-aware farming practices, farmers are faced with choosing among a plethora of innovations, from new cultural practices or cultivars to new pest management planning. In addition to these complex choices, they have to make trade-offs between production, labour, subsidies, and environmental risks (Waller et al., 1998). There is growing interest in methodologies for designing more sustainable cropping systems. Many authors have now demonstrated that crop models are useful tools for designing innovative systems (Dogliotti et al., 2003, 2004; Keating et al., 2003; Loyce et al., 2002a,b; Sterk et al., 2006; Stöckle et al., 2003; Tixier et al., 2008a). Nevertheless, published approaches often deal with new combinations of current cultural practices and rarely with radical new technical innovations. Furthermore, these approaches do not pay attention to the diversity of farming situations to which the innovations are applied (Sterk et al., 2007).

Some innovations might be very efficient in some farming contexts and completely inadequate in others (Orr and Ritchie, 2004), mostly because of environmental conditions, economic endowments and current farming systems, which vary widely among farmers (Bernet et al., 2001). This context is not taken into account to an appropriate extent and most agronomists tackle only one or a few theoretical situations that can be unrealistic and often not well described (Sterk et al., 2007). Hence, the assessment of innovative cropping systems may be biased. Thus, evaluating *ex ante* the production and the environmental performances of innovations in the specific context of each farm type becomes an important part of prototyping new cropping systems that target high productivity and are more environmentally friendly. This evaluation is the key point that helps researchers and stakeholders promote innovations for farms where they are most suitable and to guide the dissemination and the adoption of innovations (Diederen et al., 2003).

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However, adopting an innovation also depends on many factors, e.g., social, economic, or personal (Edwards-Jones, 2006). In this study, we focus on production and environmental performances of innovative cropping systems.

When a farmer integrates an innovation into their current cropping system, this integration usually requires some adaptation resulting in an innovative cropping system specific to the farm type. The conditions of a farm include a biophysical context, i.e., climate, soil type, plant-parasitic pressure, and a technical context, i.e., level of inputs, labour, and technical knowledge. In a given production area, there is often a wide range of farm types. This diversity in farm types is generally even greater in tropical conditions. Technical innovations are the basis of progress in cropping systems; they include genetic innovations such as pest resistant varieties, intercropping, integrated pest management, new type of fertilization, or new crop rotations. Innovations provide different economic and ecological services, e.g., increased yield, reduced pesticide uses, and protection against erosion and runoff.

Throughout the world, banana production (*Musa* spp., AAA, Cavendish sub-group cv. Grande Naine) for export is mainly based on intensive monocropping systems. There is a wide range of production types, from organic to high input systems. However, most intensive systems are not environmentally friendly. The agronomic and ecological sustainability of these systems is often hampered by a high level of root parasitism, including nematodes (Tixier et al., 2007b). Air, soil, and water quality may be adversely affected by the frequent applications of chemical pesticides that are required to control parasitism and by soil and plant management practices that may lead to severe erosion. These risks are magnified in fragile, tropical, insular conditions such as those found in Guadeloupe, in the French West Indies (F.W.I., 16°15′N, 61°32′W), where inhabited areas, coral reefs, and rainforests are located close to agro-systems (Bocquene and Franco, 2005; Bonan and Prime, 2001). This issue also concerns all areas of intensive production of banana (Castillo et al., 2006; Chaves et al., 2007; Matthews et al., 2003). At the same time, managing the labour, adapting to a fluctuating and highly competitive market, and limiting pesticide use are major economic problems that threaten the entire banana production sector in F.W.I. (Bonin et al., 2004). In the specific case of Guadeloupe, there is a wide range of farm types, from the intensive systems similar to the ones in intensive production areas of Latin America to very extensive systems with very low input, similar to the ones found in a small rural farm context.

In this paper, we present the *ad hoc* adaptation of the crop model SIMBA (Tixier et al., 2008a) and a method to evaluate several innovations in six types of farms in Guadeloupe that have been previously identified through a typology of banana farming systems. The SIMBA model was chosen for this study as it allows us to account for a wide range of technical operations. We then present a detailed evaluation of 16 innovations with regard to yield and pesticide use for six farm types. We analyze the performances of these innovations relative to current cropping systems. In the perspectives, we highlight how model-based evaluation of innovation can interact with farm- and landscape-scale prototyping methods. To our knowledge, this is the first time that a biophysical model-based approach has been used to assess innovations in the context of different farm circumstances.

2. Materials and methods

2.1. Current cropping systems and farm context

In Guadeloupe, banana-based cropping systems range from very intensive to very extensive. A typology of these cropping systems has been published previously (Blazy et al., 2008).

This typology was derived from a cluster analysis based on data collected from a sample of 67 banana growers in the territory, which represents a sampling rate of 25%. The variables used in the statistical analysis for the grouping of farms into few farm types were selected to describe the technical management of banana and the environmental and socio-economic conditions of the farm. This has led to the definition of six farm types (Table 1). The most intensive farm types (1–4) use a high amount of fertilizer, pesticides, labour, and frequent replanting with ploughing, and are characterized by a wide range of agronomical performances (from 21 to 46 tons ha^{-1} year^{-1}). On the other hand, the less intensive farm types (5 and 6) are low-input perennial systems that are less harmful to the environment but have a very low level of production (15.8 and 18.5 tons ha^{-1} year^{-1}). All these farm types also have different flexibility for innovation as they differ in production factors like labour, land, access to information, and financial resources. For this reason, a high number of modalities of innovation have been tested in this study. For this modelling study, we defined one theoretical farm for each farm type. For every technical decision rule and soil and climate condition, we selected the mean or the modal value of each farm type. These mean values were extracted from the 67-farm database used to build the typology (Blazy et al., 2008), in which each farm type has very low intraclass variability.

2.2. Soil and climate conditions of banana cropping systems in Guadeloupe

Table 2 presents the climate, soil, and topographic characteristics of each farm type. There is a correlation between the farm types we defined and the altitude. For example, the most productive types are at low altitude (below 300 m for types 1–4), while the less productive types are at higher altitudes (above 300 m for types 5 and 6). All the farms are based on volcanic ash soils. Type 2 is mainly found on ferralitic soils that are old and compacted, with 2795 mm of rain annually, which makes it susceptible to drought. Types 4–6 are at higher altitude on andisols that are less evolved and characterized by fast drainage in areas that receive 3500 mm of rain annually, ensuring no risk of drought in this area. Types 1 and 3 are on nitisols, which are mid-evolved soils in areas that receive 2700 mm of rain or less annually. In these areas, there is a risk of drought, which is minimized by irrigation for type 3. Temperature and sunlight vary little across farm types. Variations of environmental conditions can be explained by spatial heterogeneity of farms location, mainly in terms of altitude and exposure to sun and wind. For all these systems, root nematode pressures differ considerably (Clermont-Dauphin et al., 2004). This distribution emphasizes the fact that the more competitive innovations cannot be the same for all farm types.

2.3. Innovative cropping systems

We assessed 16 innovations: 13 single innovations (innovations that only concern one component of the cropping system) and three integrated innovations that combine single innovations. Table 3 presents the characteristics of the 16 innovations and their agro-ecological services. Innovations A1, A2, and A3 consist of stopping the use of pesticides (nematicides and herbicides); they can be considered innovations based on extreme societal regulation in comparison with the current practices. Innovations, B1, B2, and B3 consist of rotations with fallows improved by cover crop (*Crotalaria juncea*), regular fallows that use herbicides, and an 18-month rotation with pineapple. These cover crops help reduce the plant-parasitic nematode population during fallows, thus shortening fallows before banana plants are planted. Innovations C1, C2, and C3 are based on intercropping with *Canavalia ensiformis*, *Brachiaria decumbens*, and *Impatiens* sp.; they are currently under

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Table 1
Characteristics of the banana management systems of the farm types in Guadeloupe.

Variable	Unit	Farm type					
		1	2	3	4	5	6
Regional importance							
Fraction of population	%	14	32	6	28	6	14
Fraction of banana area	%	4	14	30	44	5	3
Banana management system							
Proportion of banana areas replanted each year	%	21	15	15	16	0	0
Rate of seedlings that are produced by tissue culture and are nematode-free	%	50	40	100	90	0	0
Nitrogen applied per plant per application	kg	0.100	0.100	0.100	0.100	0.205	0.100
Number of nitrogen applications each year	year^{-1}	12.0	9.0	17.0	12.0	3.0	6.0
Number of herbicide treatments per year	year^{-1}	4.8	6.0	5.0	6.0	0.0	4.0
Number of nematicide treatments per year	year^{-1}	1.0	1.5	2.5	1.0	0.0	1.0
Rate of banana plants replaced each year	%	11	11	9	5	12	15
Amount of post-flowering work to bunches for banana quality management	d ha^{-1} year^{-1}	47	32	44	38	32	43
Rate of anchored flowered plants for down beating limitations (using guy ropes)	%	50	80	100	100	15	7
Type of destruction of banana fields before replanting: mechanical, chemical, or manual	–	Mechanical	Mechanical	Mechanical	Chemical	None	None
Type of tillage at plantation: mechanical or manual	–	Mechanical	Mechanical	Mechanical	Mechanical	Manual	Manual
Rotation presence: equals 1 if fallow or rotations present in banana annual rotation; otherwise 0	–	0	0	1	1	0	0
Fungicide treatments: equals 1 if fungicide treatments are done (5 per year) otherwise 0	–	1	1	1	1	0	0
Cropping system performances							
Average yield of banana cropping system	tons ha^{-1} year^{-1}	21.0	23.5	46.0	38.5	15.8	18.5
Amount of active mater of biocides applied each year	kg ha^{-1} year^{-1}	26.8	30.4	29.7	22.9	0.0	12.1
Annual profit margin	€ ha^{-1} year^{-1}	2097	760	4929	4849	−971	1235

investigation and their aim is firstly to reduce herbicide uses and secondly to improve soil nitrogen status. Innovations D1 and D2 are modifications of decision rules for application of nematicides and herbicides according to a monitored threshold of plant-parasitic nematodes and a percentage of soil covered by weeds. Innovations E1 and E2 are based on resistant cultivars; two types of resistant crops have been defined according to characteristics of synthetic hybrids under development (Abadie et al., 2007; Bakry et al., 2007). These two types have been defined as resistant to the Sigatoka Disease and Black Leaf Streak Disease, caused by *Mycosphaerella musicola* and *Mycosphaerella fijiensis*, respectively. In addition to these desired features, they are less susceptible to plant-parasitic nematodes, mostly burrowing (*Radopholus similis*) and lesion (*Pratylenchus coffeae*) nematodes, than the classic Cavendish cultivars (Quénéhervé et al., 2009). Finally, they have a different development and growth pattern, with a shorter cropping cycle and smaller weight of fruit bunches. They differ from each other in the level of these two characteristics. The three integrated innovations (F1, F2, and F3) were designed with a combination of rotations, intercropping, no-tillage, organic fertilization, or resistant varieties.

2.4. *The SIMBA model and its new features*

SIMBA simulates banana cropping systems at field level over several cropping cycles. It includes sub-models that simulate soil structure, water balance, root nematode populations, yield, and economic outputs with a sound balance between representing the major processes of the system in the region and keeping the model simple to reduce the parameterization costs in a large range of conditions (Tixier et al., 2008a). The choice of the SIMBA model was also motivated by its mechanistic structure with dynamically interlinked sub-models, which allows for a good representation of different treatments with their interactions. SIMBA and all of its modules run at a weekly time-step at the field scale. All modules were calibrated using data previously collected in F.W.I. SIMBA was developed in the STELLA$^{®}$ software version 7.0.2 from Isee systems (formerly High Performance System$^{®}$). In SIMBA, all practices are described by ‘decision rules’, which are composed of a decision variable, a control variable, and an activation threshold or variation range. Such rules are coded with ‘if – then – else’ algorithms.

The main feature added in the SIMBA model for this study is the nitrogen balance module, SIMBA-N (Dorel et al., 2008). The other main additional feature is the intercrop module SIMBA-IC, which is based on the simulation of leaf area index (LAI) and vegetative dry matter. The principles of this module are similar to those used in STICS (Brisson et al., 2004). The net primary production and the LAI are calculated based on the interception of the photosynthetically active radiation (PAR) accounting for the interception by the banana canopy. The percentage of nitrogen in cover crops is accounted for by uptake of mineral nitrogen from soil and restitution into the soil

Table 2
Mean environmental conditions of each farm type.

Environmental condition variable	Unit	Farm type					
		1	2	3	4	5	6
Annual rainfall	mm year^{-1}	2614	2795	2700	3542	4118	4610
Sunlight	MJ m^{-2} day^{-1}	18.1	17.5	17.5	15.4	17.3	12.7
Temperature	°C day^{-1}	25.7	25.4	25.4	24.4	22.9	23.0
Soil type	–	Nitisol	Ferralitic	Nitisol	Andisol	Andisol	Andisol
Mean slope	%	10	0	10	10	20	30
Mean altitude	m	80	115	123	250	550	380

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Table 3
Main characteristics of the innovations.

Innovation type	Innovation description	Innovation code	Agro-ecological services						
			Reduce nematicide	Reduce herbicide	Reduce fungicide	Natural control of nematode	Natural control of weed	Nitrogen fixation	Improving crop tolerance to nematodes and fungi
A. Societal regulations	Nematicide stopping	A1	X						
	Herbicide stopping and mechanical weeding	A2		X					
	Nematicide and herbicide stopping and mechanical weeding	A3	X	X					
B. Rotation or improved fallow	8 months of improved fallow with *Crotalaria juncea* before replanting	B1	X			X		X	
	12 months of chemically controlled fallow before replanting	B2	X			X			
	18 months of rotation with pineapple	B3	X			X			
C. Intercropping	Intercropping with *Canavalia ensiformis* and mulching at flowering	C1		X			X	X	
	Intercropping with *Brachiaria decumbens* and mechanical mowing	C2		X			X		
	Intercropping with *Impatiens* sp.	C3		X			X		
D. Conditional application of pesticides	Nematicide treatment as a function of nematode pressure	D1	X						
	Herbicide treatment as a function of soil cover	D2		X					
E. Resistant cultivars	Cultivar type 1	E1	X		X				X
	Cultivar type 2	E2	X		X				X
F. Integrated systems	12 months of improved fallow with *B. decumbens* before replanting + no tillage + intercropping with *B. decumbens*	F1	X	X		X	X		
	12 months of natural chemically controlled fallow before replanting + intercropping with *Impatiens* sp.	F2	X	X		X	X		
	Cultivar type 2 + 8 months of improved fallow with *C. juncea* before replanting + intercropping with *C. ensiformis* and mulching at flowering + organic fertilization	F3	X	X	X	X	X	X	X

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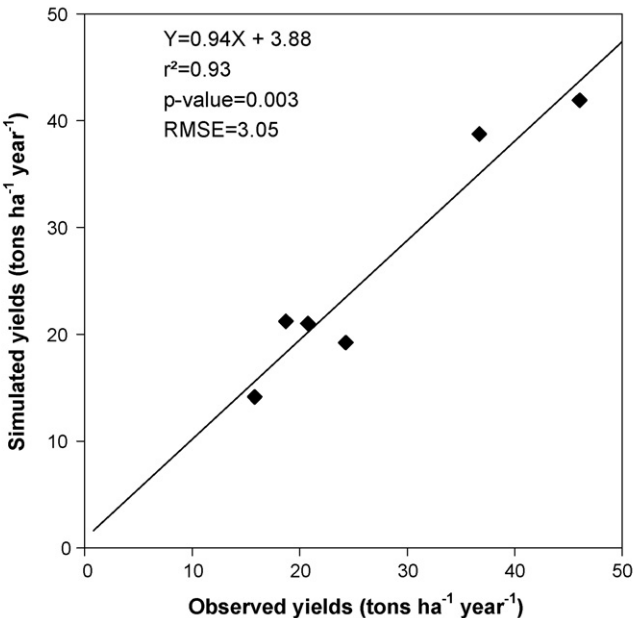

Fig. 1. Relation between yield simulated with the SIMBA model and yield observed in the six farm types.

organic pool. The nitrogen atmospheric fixation is also included in the SIMBA-IC module as a fixed rate depending on species.

2.5. Model calibration and testing

Most parameters of the SIMBA model were previously calibrated (Dorel et al., 2008; Tixier et al., 2004, 2006, 2007a, 2008a) and were kept the same for this study. The parameters of the new components of the SIMBA model were calibrated using data issued from the literature and from unpublished experimental trials. Cover crops *B. decumbens*, *Impatiens* sp., and *C. ensiformis* were calibrated by fitting to field trials with data from Achard (pers. com.), Dorel (pers. com.), and Tournebize (pers. com.), respectively. New cultivar types were calibrated to have different development, growth, and resistance to pests (Tixier et al., 2008b). Types 1 and 2 have partial resistance to *M. musicola* and *M. fijiensis*, are sufficiently tolerant to the nematode *R. similis* to stop fungicide and nematicide, have a bunch weight reduced by 30% and 20%, respectively, and have a planting-harvest interval reduced by 40% and 20%, respectively.

In addition to the module-by-module validation performed previously (Dorel et al., 2008; Tixier et al., 2004, 2006) and to the broad yield validation already performed (Tixier et al., 2008a), a new evaluation of the SIMBA model was carried out on the yield for the farm types defined in this study. For this, the measured yields for the six types of farms described in Table 1 were compared to the yields simulated with SIMBA using a set of inputs (sets of decision rules, soil, and climate parameters) representative of each farm type. There is a significant linear correlation between the measured and simulated yield for the six farm types ($r^2 = 0.93$; p-value = 0.003; Fig. 1). The equation of the linear correlation shows a slight overestimation of the yield by the model (intercept at 3.88 tons ha^{-1}), while the slope is almost 1 (0.94). The root mean square error (RMSE) is 3.05 tons, which is what can be expected for a crop model in comparison with the average yields of between 15.6 and 46 tons ha^{-1} depending on farm type (Table 1). We therefore consider the model as valid for the current practices over the wide range of soils, climates, and technical contexts covered by the six farm types. This validation was not possible for innovations such as intercropping, rotations, or new cultivars because farmers have not yet applied these innovations in all farming situations. Although the aim of our modelling approach was to provide information that cannot be collected from a farmer survey, we confronted the model's outputs with farmer's observations for the few existing "innovative" cropping situations in the territory. First, we identified a set of farmers who are currently trying some innovations. It allowed us to identify four "innovative" cropping situation (stopping nematicide treatment, planting banana in rotation with *B. decumbens*, intercropping banana with *C. ensiformis* after a fallow period, and intercropping banana with *impatiens* sp.). Then, we confronted the model's outputs in terms of impact on yield with the farmers' observations. For the four innovative cropping situations that we have been able to test with this approach, farmers agreed with model's predicted tendencies for each case, indicating that this model was able to provide consistent information for assessing the impacts of innovative cropping systems tested under real farming conditions. The question of model validation in such a study will be discussed in Section 3.4.

2.6. Evaluation of innovative cropping systems

To assess all the innovations in every context provided by the six farm types, we followed a three-step procedure:

- Initializing the model's inputs for each farm type, as described in Table 2. These inputs include the soil, climate, and slope characteristics of the field to be simulated.
- Initializing the model's input parameters for each farm type, as described in Table 1. This includes the decision rules that describe the banana management systems, according to a conditional 'if-then-else' formalism (Tixier et al., 2008a).
- Overwriting the technical decision rule parameters by the ones that describe the technical innovation to be tested. Some innovations can interact indirectly with other components of the system to build a global new consistent management system, e.g., adopting intercropping deactivates herbicide treatments and adopting rotation or improved fallow deactivates nematicide treatments during the 3 years following banana planting.

This three-step procedure makes it possible to conduct an *ex ante* 'Farm type × Technical innovation' assessment and can be used to pinpoint technical innovations that could subsequently be tested in the field.

We did not take into account the inter-annual variation of climate, but we used a climate dataset representative of a mean year, with intra-annual variations of climate at weekly step for each farm type. These climates were obtained by defining an average climate through 10 years of data collected from an agro-ecological network of meteorological stations 'RAINETTE' (RAINETTE, 2008). The study has been conducted in a tropical region where yearly variations of climate are much lower than in temperate climates. For instance, the coefficients of variation of temperature and sunlight calculated over the period 1997–2007 were 1% and 6%, respectively. This coefficient is higher for rainfall (48%), but a deeper analysis of yearly variations of rainfall measured between 1997 and 2007 revealed that the risk of water stress is small. Banana producers are located in a region where rainfall is generally higher than banana's crop demand, which is about 2100 mm year^{-1} (Lassoudière, 2007). Types 4–6 are all located in areas where there is no risk of water stress. Type 3 has the possibility of using irrigation. Types 1 and 2 are located at an altitude of about 100 m and are the only ones that could suffer from a lack of rainfall. However, the study of yearly climate variations in this area revealed that rainfall was less than that needed by banana plants for only 2 years out of the 11 analysed, with a total rainfall of 1875 mm for the year 2007 and 1078 mm for the year 1997 (RAINETTE, 2008). Therefore, considering that the risk of water stress was low, and in order to limit the number of

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simulations performed to assess the impacts of all innovations on each farming situation, we decided to use average weather conditions.

The yield and the amount of pesticide active ingredient used were stored at every step of the simulations in an output-database. In the final analysis, the yield and the amount of pesticide active ingredient used were summed over the cropping period in order to obtain a single value for these two variables. Although more than one pesticide was used by farmers and the correspondent active ingredients can be harmful to environment in different ways, we chose to sum them. This allows for the assessment of the reduction of reduction of total pesticide use according to policy makers indicators. According to IFEN (2007), the sum of all pesticide active ingredients should be less than 0.5 μg l^{-1} for groundwater and 2 μg l^{-1} for surface water to be considered as drinkable.

We evaluated the 16 innovations presented in Table 3 in the context of the six farm types and in comparison with the current ones.

3. Results and discussion

3.1. Impact of innovations on yield for different farm types

Table 4 shows, for a given farm type, the variation between the yields of innovations compared to the yield of the current cropping system. Yield gain of innovative systems varied between −23.6 tons ha^{-1} year^{-1} for type 3 and innovation E1 and 15.9 tons ha^{-1} year^{-1} for farm type 5 and innovation C1. The biggest yield reductions were observed for new cultivars because of their smaller bunch size. Yield increased more (i) for rotations and for the integrated systems, except for the one using new cultivars, in the case of farm types 1 and 2 because of the significant reduction of nematode populations, and (ii) for intercropping with *C. ensiformis* in the case of extensive systems because of the additional nitrogen provided by the legume plant. In all farm types, some innovations increased the yield while others decreased it. The confrontation between innovations and farm types allow for the definition of four kinds of innovations:

- innovations that had a positive effect on yield for some farm types and negative effect on the yields of other farm types (e.g., B3 and, in a less contrasted way, B2, F1 and F2).
- innovations characterized by a null constant effect on the yield independently of the farm type; e.g., innovations A1, A2, A3, C2, C3, D1, and D2.
- innovations leading to a general yield increase for all farm types (e.g., C1 and B1).
- innovations leading to a general yield decrease for each farm type (e.g., E1, E2 and F3).

To illustrate these four types of innovations, we show in Fig. 2 the evolution of the simulated impacts on yields for innovations C1, C3, E2 and B3 compared to the yields measured in current cropping systems. Innovation C1 (intercropping with *C. ensiformis*) had an effect on the yield that varied from +4.4 to +15.9 tons ha^{-1} year^{-1} across the six farm types, while innovations C3 and E2 had an effect from −0.1 to +0.4 tons ha^{-1} year^{-1} and from −4.2 to −16.1 tons ha^{-1} year^{-1}, respectively. In the case of innovation C1, there was a negative correlation between the simulated yield gain and the yield in current cropping systems ($Y = 1.97 + 2850/X^2$; $r^2 = 0.78$). We hypothesize that the gain in yield is larger when the yield of the current farm type is low, as observed in other studied on crop management systems prototyping (Lançon et al., 2007). Analysis of the impact of innovation E2 revealed a linear negative regression, indicating that the higher is the current yield, the higher the impact on yield. The slope of the linear regression indicates that yield decrease is about 65% ($y = -0.35x - 0.58$; $r^2 = 0.9134$).

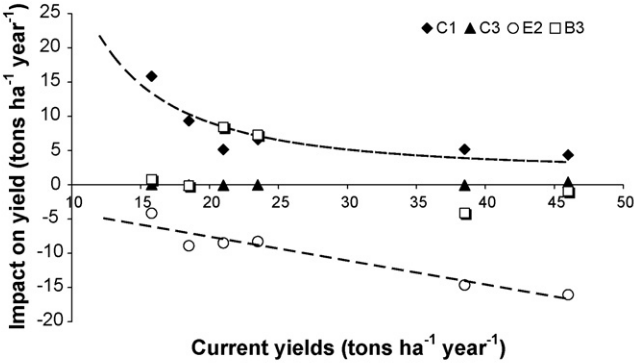

Fig. 2. Evolution of the simulated yields gains of innovations C1, C3, E2 and B3 compared to the yields of the current cropping systems. *Note*: Dotted curves are regression curves fitted for innovations C1 and E2. Equation regression C1: $Y = 1.97 + 2850/X^2$; $r^2 = 0.78$; equation regression E2: $Y = -0.3494x - 0.5827$; $r^2 = 0.91$.

It is interesting to denote that stopping nematicide treatments would induce only a few yield reductions (Table 4). This is probably because farm types 3 and 4 already practice fallow and would not need to use nematicide, whereas those that do not practice any rotation apply too little nematicide to be effective in controlling nematode pressure (farm types 1 and 2).

3.2. Impact of innovations on the pesticide uses for different farm types

We next evaluated the pesticide use for the 16 innovations in the context of the six farm types. Table 5 shows the variation between the pesticide use in innovative cropping systems compared to the pesticide use in the current cropping systems. In this analysis, we do not consider farm type 5, where the current cropping system is very extensive and already does not use pesticides. Reduction of pesticide use in innovations varied between −100% (total suppression) and −2% of the amount of pesticides used in the current cropping systems. Innovation A3 (stopping nematicides and herbicides), E1 and E2 (resistant hybrids) and integrated innovations F1 and F2 led to a strong reduction in pesticide uses, over 50% for each farm type, which results in a pesticide use close or below 10 kg of active ingredient use per year and per hectare for all farm types. Innovation F3 (integrated system with resistant hybrids) allows a complete stopping of pesticide uses.

3.3. Most promising innovation for each farm type and tradeoffs between yields and pesticide reduction

To identify the most promising innovations for each farm type, we identified three sets of constraints imposed by the farm context (Lançon et al., 2007) and which define the threshold of the impacts of innovations on yields and on pesticide uses to accept or reject this innovation for this farm type. In this analysis, impacts of innovations were expressed as relative impacts as follows: ((yield with innovation − yield of current cropping system)/yield of current cropping system) and ((pesticide use with innovation − pesticide use with current cropping system)/pesticide use with current cropping system). Such expressions were used in this analysis because they have been frequently used by policy makers since the objective of a 50% reduction in pesticide use by 2018 was been defined (Sénat, 2008). For farm types 1 and 2, which have low yields and a high level of pesticide uses, we chose to select innovation pairs that lead to a minimum increase in yield of 25% while decreasing the use of pesticides by at least 25%. For farm types 3 and 4, which show high yields

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Table 4
Impact of innovations on yield at field level compared to the standard cropping system for all farm types. For each farm type, the three best innovations are in bold.

Innovation	Farm type (current yield expressed in tons ha^{-1} year^{-1})						Mean value	Standard error
	1 (21.0)	2 (23.5)	3 (46.0)	4 (38.5)	5 (15.8)	6 (18.5)		
A1	−0.2	−0.4	−0.6	−0.2	0.0	−0.2	−0.3	0.2
A2	0.0	0.0	0.4	0.0	0.0	0.0	0.1	0.2
A3	−0.2	−0.4	−0.2	−0.2	0.0	−0.2	−0.2	0.1
B1	**15.3**	**12.5**	**3.1**	**5.3**	**2.6**	**3.0**	7.0	5.5
B2	**11.7**	**8.8**	−0.1	1.0	1.4	0.9	3.9	5.0
B3	8.4	7.3	−4.1	−1.0	0.8	−0.1	1.9	4.9
C1	5.1	6.6	**4.4**	**5.2**	**15.9**	**9.3**	7.7	4.3
C2	−1.3	−0.7	−1.0	−1.3	0.2	−0.2	−0.7	0.6
C3	−0.1	0.0	0.4	−0.1	0.0	0.0	0.0	0.2
D1	−0.2	−0.4	−0.6	−0.2	0.0	−0.2	−0.3	0.2
D2	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.1
E1	−13.4	−12.1	−23.6	−22.1	−7.2	−14.0	−15.4	6.3
E2	−8.5	−8.3	−16.1	−14.6	−4.2	−8.9	−10.1	4.4
F1	**11.5**	**9.7**	−0.6	**2.0**	**2.3**	**1.7**	4.4	4.9
F2	**11.5**	8.6	−0.2	0.8	1.4	0.6	3.8	5.0
F3	−2.7	−1.1	−15.4	−14.8	−1.2	−7.8	−7.2	6.6

Table 5
Impact of innovations on pesticide uses at the field level compared to the standard cropping system for all farm types. For each farm type, the three best innovations are in bold.

Innovation	Farm type (current pesticide uses expressed as a sum of active ingredient in kg ha^{-1} year^{-1})					
	1 (26.8)	2 (30.4)	3 (29.7)	4 (22.9)	5 (0.0)	6 (12.1)
A1	−5.5	−8.3	−11.9	−3.9	0.0	−5.6
A2	−8.2	−9.2	−6.8	−7.9	0.0	−6.5
A3	−13.7	−17.5	−18.8	−11.8	0.0	**−12.1**
B1	−6.1	−6.4	−4.1	−0.5	0.0	−2.5
B2	−7.2	−7.5	−5.5	−1.6	0.0	−2.9
B3	−10.0	−10.3	−9.0	−4.2	0.0	−3.9
C1	−8.2	−9.2	−6.8	−7.9	0.0	−6.5
C2	−8.2	−9.2	−6.8	−7.9	0.0	−6.5
C3	−8.2	−9.2	−6.8	−7.9	0.0	−6.5
D1	−5.5	−8.3	−11.9	−3.9	0.0	−5.6
D2	−7.5	−8.6	−6.2	−7.4	0.0	−6.1
E1	**−18.6**	**−21.2**	**−22.9**	**−15.0**	0.0	−2.6
E2	**−18.6**	**−21.2**	**−22.9**	**−15.0**	0.0	−2.6
F1	−15.6	−19.1	−18.5	−11.6	0.0	**−12.1**
F2	−15.9	−19.3	−18.8	−11.8	0.0	**−12.1**
F3	**−26.8**	**−30.4**	**−29.7**	**−22.9**	0.0	**−12.1**

and pesticide use levels, we chose to retain those innovations that lead to a minimum decrease of 25% in pesticide use while keeping at least 95% of current yields. The 5%-yield losses were considered acceptable for these types because they already have high yield and the savings on inputs can compensate this possible loss. For farm types 5 and 6 that have low yields and pesticide use levels, we considered as promising innovations those that lead to an increase of at least 25% in the current yields without increasing the use of pesticides. A summary and results of this procedure are presented in Fig. 3 and Table 6. For each farm type, the most promising innovations are located on the right of the vertical dotted line and below the horizontal dotted line in Fig. 3.

The number of innovations that match the criteria established varied from only one for farm types 5 and 6 up to eight innovations for farm type 4, showing that the scope for innovating can vary considerably across farm types. The most promising innovations for farm types 1 and 2 include rotations (B2, B3, F1 and F2). For farm types 1 and 2, rotations are the key practice to be incorporated into their crop management systems to control nematode pressure; thus allowing the reduction of pesticide use and increased yields. The innovation C1 (intercrop with *C. ensiformis*) is also interesting for farm type 2 because it uses a low level of nitrogen fertilizers and benefits more from increased nitrogen input provided by this legume cover crop.

Innovations that consist in reasoning or stopping pesticide use (innovations from types A and D in Table 3) are promising for farm types 3 and 4. For type 3, this could be because nematicide use is not necessary since crop rotations are already used. It is interest-

Table 6
Yields and pesticide use impact thresholds for selecting promising innovations, matching innovations and regression between the effect of innovations on the yield (x) and the effect of innovations on the pesticide uses (y) for each farm type. *Note*: to be selected, an innovation should exceed the yield impact threshold and be below the pesticide use impact threshold.

Farm type	Yields' impacts threshold	Pesticide uses' impacts threshold	Matching innovations	Equation of the linear regression	r^2	p-Value
1	25%	−25%	B2 B3 F1 F2	$y = -0.452 + 0.221x$	0.13	0.171
2	25%	−25%	B3 C1 F1 F2	$y = -0.466 + 0.302x$	0.14	0.158
3	−5%	−25%	A3 D1 F1 F2	$y = -0.351 + 1.168x$	0.56	0.001
4	−5%	−25%	A2 A3 C1 C2 C3 D2 F1 F2	$y = -0.327 + 0.906x$	0.52	0.002
5	25%	0%	C1	Not performed	–	–
6	25%	0%	C1	$y = -0.557 - 0.167x$	0.03	0.550

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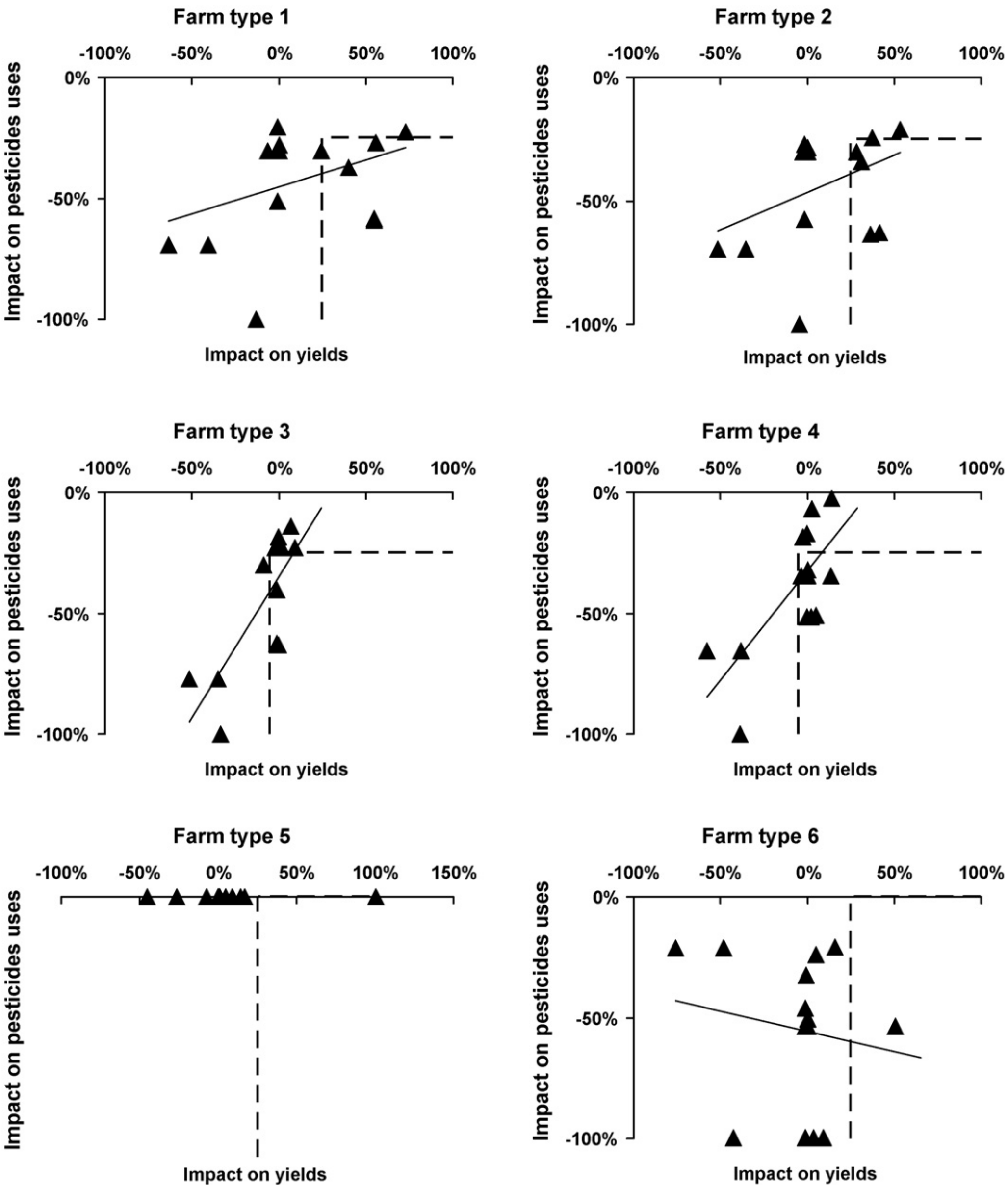

Fig. 3. Impacts of innovations on pesticide uses and on yields for each farm type. *Note*: Thresholds to select promising innovations defined in Table 6 are represented by dotted lines. For each farm type, promising innovations are on the right of the vertical dotted line and below the horizontal dotted line.

ing to observe that, although rotations and intercroppings do not individually satisfy the set of constraints, they do satisfy it when combined into integrated systems (e.g., for farm type 2, B2 and C3 do not satisfy the set of constraints, but F2 does). This shows that, for some situations, sustainable systems can only be achieved by combining different technological innovations. Compared to farm type 3, farm type 4 shows a larger scope for innovation since all kinds of intercropping seem to be promising technologies for this farm type. The environmental characteristics of farm type 4, with deeper soils and a higher rainfall, could represent ideal conditions for the cultivation of the tested cover crops, while these innovations allow drastic reduction of pesticide use (−34%). For farm types 5 and 6, the most promising innovation is the use of intercropping with the legume crop *C. ensiformis* because it improves nitrogen nutrition.

It is interesting to pinpoint that innovations based on the use of disease resistant cultivars (E1 and E2) were not selected as promising innovations for any of the farm types, mainly because of decreased yields. Breeders will have to focus on the bunch size as an important criterion before disseminating these varieties as innovations. Integrated systems F1and F2, which are the most efficient ways to reduce pesticide use, satisfy the set of constraints for farm types 1–4.

Next, we sought to determine whether there was a trade-off between pesticide reduction and yield variation for each farm type separately (see regression curves of these two variables in Fig. 3 and equations in Table 6). There is a significant positive correlation for farm types 3 and 4, which are the two most productive ones (slopes of 1.168 and 0.906, respectively). This result shows that the more productive the farm, the higher the decrease in yield caused by 'environmentally friendly innovations'. This could be explained by Liebig's law of the minimum, considering that, at low yields, other limiting factors unaffected by the innovation may be controlling yield.

These findings support the hypothesis that some innovations are more efficient (increased yield and reduced pesticide use) for some farm types. Nevertheless, the number of promising pairs of innovation-farm type is small (22) compared to the total number of

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pairs evaluated in our study (96). This reinforces the need for exploring a wide range of innovations in order to increase the probability of fitting with the specific context of each farm type and hence increase the likelihood of adoption. Furthermore, for a single type of innovation (e.g., intercropping or improved fallow), one variant can be promising in a farm type while another is not, and vice versa in another farm type (e.g., C1 is promising for farm type 5 while B3 is not, where the opposite is true for farm type 1). Finally, the results show that, despite an apparent trade-off between yield and pesticide uses, there are some innovations that can address both production and the environmental issues.

3.4. Limits and perspectives

The main limit of our results lies in the validity of the model, within the innovation-soil-climate-technical context range explored in this study. Although there is good precision for the yield of current cropping systems (Fig. 1) and the model tested on a few innovative cropping situations agrees with farmer's observations, it is difficult to validate the simulation of innovations in farming contexts where these innovations have never been tested. This issue underlines the difficulty for researchers to know how much they can trust models when they are testing innovations in the specific context of a farm.

A more extensive evaluation of the model is therefore needed before using these types of results to disseminate innovations. The results obtained with the use of the model allow the generation of hypotheses that could subsequently be tested in the field or in small-scale trials.

It would also be interesting to use the model to test extreme climatic years, to explore the sensitivity of the results to the weather scenario adopted, e.g., a very low level of rainfall for farm types 1 and 2. For instance, performances of intercropping systems could be strongly modified for extreme climates, such as drought years. Similarly, innovations that reduce erosion will be particularly important in those years when it is a problem and pesticide leaching can depend on the amount of rainfall.

Nevertheless, this does not reduce the value of the methodology proposed in this study using the SIMBA model. This model was especially designed for the banana-based systems; it thus efficiently accounts for the specificities of the banana crop, e.g., unsynchronized plant population, but also the specificities of the management of the system by the farmer. Hence, it appears to be well adapted to the assessment of technologies contextualized in the biophysical and the technical parameters of a given farming situation. The cropping system functioning include interactions between biophysical processes and technical actions; it is thus impossible to assess one technical part of the system independently of others. Biophysical models allow systemic assessment of technical innovations accounting for the technique–technique and technique–biophysical interactions.

Our simulations allowed us to identify, for different farm types, the innovations that improve sustainability of cropping systems by increasing yields while reducing pesticide use. However, this work has to be completed by a cost-benefit analysis of the alternative systems relative to the current ones (Nelson et al., 1998). For instance, fallows adoption increases yield but requires a transition period (fields are not productive during the fallow) that is critical for low-resource farmers. Economic assessment of yield benefits due to innovations should also include the cost of labour, land and inputs, over the whole crop succession (Swinkels et al., 1997). The cost of additional labour for innovation is particularly important for intercropping systems that replace pesticides by using additional labour. This additional cost may be a major issue in farming contexts of high-cost labour (Thangata and Alavalapati, 2003), as in F.W.I.

Innovation is a complex process that depends on many determinants relative to farmers' socio-economic characteristics and innovations' attributes (Abadi Ghadim and Pannell, 1999). Climatic and economic risks associated with the adoption of an innovation also have to be assessed (Marra et al., 2003). To this end, *ex ante* studies aimed at identifying farmers' constraints to the adoption of innovations should be performed using both farm surveys and on farm trials.

4. Conclusion

The simulation of innovative cropping systems with the SIMBA model demonstrates the importance of farm type in assessing yield and pesticide use for cropping systems based on low-input innovations. Some innovations in some specific farm contexts led to a benefit for both production and environmental issues. These innovations are mainly rotation or improved fallows, intercropping, and integrated systems. Even though resistant cultivars allow for considerably reduced pesticide use, field performances were radically altered by the lower yield potential. This study showed that farmers have different capacities for innovation as the number of useful innovations varies considerably among farm types according to their biophysical and technical current situations. The study of trade-offs between yield gains and pesticide reduction showed that environmentally friendly innovations cause more yield decreases in the more productive farm types. Our modelling study confirms the importance of the innovation-farm type interactions mentioned by other authors (Lançon et al., 2007) and the usefulness of models for assessing a large number of technological innovations among a wide range of biophysical and technical situations.

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