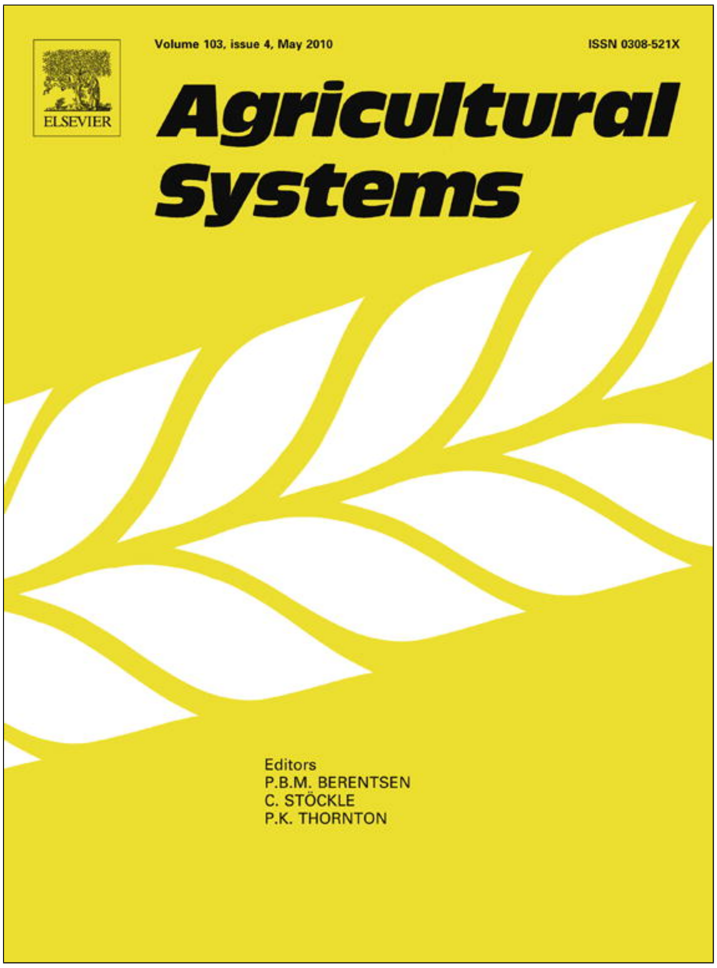
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BANAD: A farm model for *ex ante* assessment of agro-ecological innovations and its application to banana farms in Guadeloupe

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ABSTRACT

The *ex ante* assessment of innovative agro-ecological innovations is a key step in the development of more sustainable crop management systems. To this end, models are useful tools because they make it possible to rapidly assess numerous innovations in different contexts. Whereas many farm optimisation models focusing on the farmer's strategic decision to adopt new crop management systems have been published, little attention has been given to the *ex ante* modelling of the dynamic operational impacts of innovation adoption at the farm level. BANAD, a mechanistic model for such applications, is proposed. It allows the *ex ante* assessment of innovative management systems including new agro-ecological techniques, while taking into account different farming contexts and policy and market conditions. It includes three components: (i) a crop management system model, (ii) a crop model (SIMBA) and (iii) a farming system model. Our results applied to the *ex ante* assessment of six innovative banana management systems for three contrasted farm types in Guadeloupe showed that the impacts of agro-ecological innovations, which include rotations, improved fallow, intercropping, pest-resistant cultivar, and an integrated organic system, can vary considerably according to (i) the farm type in which the innovation is integrated, (ii) the nature of the agro-ecological innovations, and (iii) the criteria considered and the temporal horizon of the assessment. Innovative intercropping systems that were effective at the field level in terms of the yield improvement and decreased pesticide use could be problematic at the farm level because they increased the workload and decreased income. The adoption of rotations or improved fallow seemed to be relevant for smallholders but could induce a critical period of 1.5–2.5 years during which income decreased drastically. Under certain conditions of markets and subsidies, very environmentally friendly innovations that are less productive can however be economically effective.

1. Introduction

Climate change, increasing societal demand for cleaner production and market and policy fluctuations act on agricultural systems as driving forces because they create new production conditions that make conventional agricultural systems irrelevant or unfit for these new conditions (Hatfield et al., 2007). In this changing context, adopting agro-ecological innovations is a key point for farmers to maintain the economic sustainability of their farm while conforming to environmental regulations. Agronomists, ecologists and economic scientists can help farmers to innovate by developing technological innovations adapted to their problems and personal conditions. A key step in the development of alternative management systems is the *ex ante* assessment of innovations (van Ittersum et al., 2008). At a early stage of the design of alternative management systems, an *ex ante* assessment allows the identification of the critical points that have to be improved and to determine the conditions in which innovations will or will not be suitable.

Participatory on farm research is a promising approach to jointly assess the economic, biophysical and environmental impacts of innovative techniques (Vereijken, 1997; Franzel et al., 2001). Nevertheless, on-farm trials are generally considered costly

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and time-consuming to implement. For this reason, computer bio-economic models are increasingly used to design and evaluate innovative agricultural systems because they enable the *ex ante* assessment of innovations in a limited time and with few resources. Models indeed provide the opportunity to assess a considerable number of innovative options across a large range of situations (e.g., Dogliotti et al., 2004).

According to the review of bio-economic models made by Brown (2000), we can distinguish basically two main categories of models. On the one hand, the cropping system models represent in a mechanistic way the biological processes under different technical and environmental conditions to simulate agro-ecological processes. These models run at the field level and mainly focus on the biophysical impacts of innovative technologies (Tixier et al., 2008a; Keating et al., 2003; Stöckle et al., 2003; Loyce et al., 2002). Even if these models often include an economic module, they are not appropriate to assess the operational economic and technical impacts of innovations at the farm level, which is however crucial information for farmers to decide whether to adopt an innovation.

On the other hand are the economic optimisation farm models. These models are increasingly used and have been critically reviewed by Brown (2000) and Janssen and van Ittersum (2007) on their strengths and weaknesses in assessing technological innovation and policy changes. In these models, the decision-making process is seen as an optimisation problem in which the farmer has to choose the intensity of use of current and alternative production possibilities to optimise one or multiple objectives given several constraints. As mentioned by Brown (2000), the key limitation of economic optimisation models is "*in their ability to model the agro-ecological processes involved in such a way as to simulate the actual biological processes rather than simply using a fixed set of parameters for a finite set of activities derived from empirical observations*". In other reviews of bio-economic farm models, Janssen and van Ittersum (2007) noted that many studies focus principally on current alternatives and not on innovative management systems such as those involving agro-ecological techniques. Moreover, among the few studies conducted on innovative systems, the definition and description of alternative agricultural activities that form the inputs of the model are generally not explicitly described. Too many model studies do not mention the sources of their data on technical coefficients used to describe the alternative options, while many others do not explicitly discuss the assumptions in formulating their current and alternative activities. Technical coefficients are generally derived from production functions that are linear-segmented approximations of non-linear functions. These functions are difficult to establish empirically for very innovative management systems that are currently not present on real farms. At an early stage of a prototyping research program, it is indeed common to have minimal knowledge about the possible interactions among the innovative techniques and farm-specific economic and environmental contexts that may vary greatly at the regional level. Accounting for spatial heterogeneity of farms is thus necessary to assess the variability of economic and biophysical performances of innovations. This makes the estimation of technical coefficients of innovative alternatives difficult to establish and can limit the cross-pollination between the prototyping and farm modelling approaches (Sterk et al., 2007).

The objectives of this paper is to propose a simple mechanistic model named BANAD to assess *ex ante* the technical, economic and environmental consequences at the farm level of adopting innovative agro-ecological management systems for different production contexts. The BANAD model has been parameterised and evaluated for assessing several innovative prototypes of environmentally friendly banana management systems in Guadeloupe, in the French West Indies (F.W.I., 16°15′N, 61°32′W). In this tropical island, pesticide use has to be decreased because of serious environmental problems resulting from decades of intensive practices (Cabidoche et al., 2009; de Barros et al., 2009).

2. Material and methods

2.1. Overview

BANAD is a bio-economic farm model that jointly simulates the biophysical and technico-economic processes of resource management at the farm level under different scenarios of farm context and innovation adoption. It is a mechanistic model based on the available theory and knowledge of field biophysical functioning and farm management processes. BANAD is a dynamic model that runs at a weekly time-step and at the farm level, the farm being represented as a system of production processes under the control of farmer's tactical and strategic technical decisions. In this model, the strategic decision of adopting an innovation is forced by the model's user. Tactical decisions related to weekly actions are modelled with a set of decision rules. BANAD is a normative model in which the norm is the implementation of this set of decision rules. These rules result from the systemic integration of one or several innovations into the current observed practices that are adapted according to the nature of these innovations and the farm type.

Fig. 1 gives an overview of the general structure of the model. The outputs of the model are dynamic at a weekly time-step and relative to the banana production, cash flows, workload, and environmental impacts indicated with the total amount of pesticide active ingredient used. These four dimensions are key components of sustainability and of farmers' decision making for deciding whether to adopt an innovation (Gafsi et al., 2006). These outputs can be summarised at different time scales (month, year, crop rotation, transition from one crop management system to another) and spatial levels (field, groups of fields of one kind, entire farm). The inputs of the model are sets of parameters that define: (i) the farm's economic, technical and environmental characteristics; (ii) the innovative crop management system parameters; and (iii) the policy and market conditions. The model takes into account the spatial heterogeneity of farms at the regional level through different farm types. These sets of parameters are computed in a parameterisation module that allows the definition of consistent sets of parameters for each scenario of the simulation from the inputs database. Integrating an agro-ecological innovation into a crop management system indeed requires some adaptations of decision rules to make the innovative situation still consistent after adoption (e.g., adopting intercropping requires the cessation of herbicide treatments). The farm model is made of two components, a cropping system model that represents the biophysical and technical processes at the field level, and a farming system model. Following the representation of Rapidel et al. (2006), the cropping system model is represented as a biophysical crop model in interaction with a crop management system model (CMS). The crop model (called SIMBA, Tixier et al., 2008a) simulates the biophysical processes such as the crop growth, pest development and environmental impacts, and all the techniques that have an impact on these processes. The CMS model simulates all the cultural practices on the field during each week. The farming system model manages the farm level allocation of resources and combines and integrates the results from the different kind of fields present on the farm.

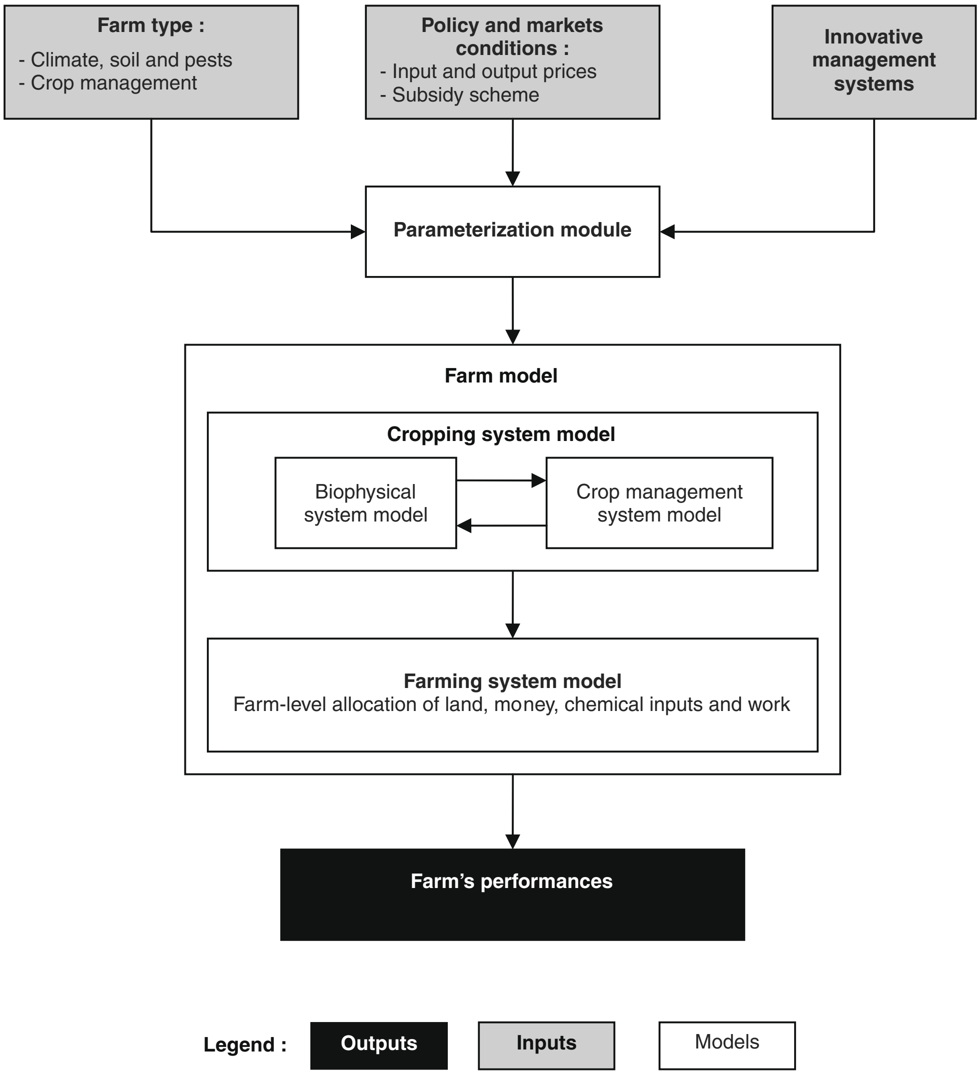

Fig. 1. The general structure of the bio-economic farm model for assessment of impacts of innovation adoption (BANAD).

2.2. Inputs

2.2.1. Farm types: crop management and pedoclimatic conditions

Inputs required to describe a farm type are relative to the bio-physical and economic parameters describing the land physical and parasitic characteristics, climate and soil types, crop rotation, management decision rules and manpower characteristics (cost and efficiency). The nature of the parameters used to model crop management are presented in a more detailed way in Section 2.2.4. In this study, the BANAD model was parameterised for three farm types that are representative of the diversity of farming situations observed in banana production in Guadeloupe (Blazy et al., 2009a). Table 1 presents the main characteristics of these farm types. Type A is a small farm (4.2 ha) located in the lowlands, with mainly familial, abundant, and low-cost manpower. It is a banana monocrop farm with replanting every 5 years. The current banana management system is of medium intensity with one nematicide treatment, five herbicide treatments, and 12 nitrogen applications per year. The farm productivity is relatively low (21 t ha^{-1}), as is the income. Type B represents large farms (82 ha) with mainly full-time permanent employees. In these farms, banana trees are currently rotated every 5 years with a 12-month fallow. It is a relatively intensive system with four nematicide treatments and five herbicide treatments each year. In contrast with other types, the agronomic and economic performances are good (33 t ha^{-1} year^{-1}; "suitable income"). Types A and B are in the lowlands with no slope and with sometimes-limited rainfall. However, only type B has access to irrigation. Type C is in the uplands at 550 m altitude, with steep slopes and abundant rainfall. It is on andisol and perennial management practices of the banana are used. This farm type is very extensive with no use of pesticide and only three applications of nitrogen per year. Its workforce is limited, the average yields are low and the economic results are negative. Three variants of these farm types named farm type D, E and F were used in this study, but only in the process of the model evaluation presented in Section 2.5. These three other farm types are described in Blazy et al. (2009a).

The three main types of soils of Guadeloupe (andisol, nitisol and ferralitic soil) were described by their porosity level, slope, depth, initial parasitic pressure and organic and mineral contents. The climatic parameters were weekly cumulated of the daily temperature, rainfall, and solar radiation. The sets of parameters used in this study were obtained by analysing a 10-year database of local climatic parameters collected by a network of meteorological stations (Rainette, 2008).

Table 1
The characteristics of the three types of farms simulated in this study.

Category	Characteristics	Units	Type A	Type B	Type C
Farm production factors	Farm acreage	ha	4.2	82.0	8.0
	Mean cost of manpower	€ day^{-1}	32.6	61.1	40.8
	Work resources	d ha^{-1} year^{-1}	178.6	136.5	104.7
Environmental conditions	Mean annual rainfall	mm year^{-1}	2614	2700	4118
	Mean sunlight	MJ m^{-2} day^{-1}	18.1	17.5	17.3
	Soil type	–	Nitisol	Nitisol	Andisol
	Mean slope	%	10%	10%	20%
	Mean altitude	m	80	123	550
Crop management system	Fallow duration	week	0.0	52.0	0.0
	Delay before replanting	year	5.0	5.0	10.0
	Nitrogen applied per plant per application	g pl^{-1}	15	15	30
	Number of nitrogen applications per year	year^{-1}	12	17	3
	Number of herbicide treatments per year	year^{-1}	5	5	0
	Number of nematicide treatments per year	year^{-1}	1	4	0
	Type of destruction of banana fields before replanting	–	Mechanical	Mechanical	Manual
	Type of tillage at plantation	–	Mechanical	Mechanical	Manual
Farm performances	Amount of active ingredient of pesticide applied per year	kg ha^{-1}	27	30	0
	Average banana production at the farm level	10^3 kg ha^{-1} year^{-1}	21	33	16
	Net income indicator (provided by farmer)	–	Little income	Suitable income	Deficit

Note: Adapted from Blazy et al. (2009a).

2.2.2. Innovative management systems

The model was initially developed to assess eighteen innovative management systems involving the adoption of rotations or improved fallow, intercropping, new pest-resistant cultivars, decrease or cessation of pesticide use, and organic fertilisation. In this paper we present only the results of the assessment of the six most promising and contrasted innovations (Blazy et al., 2009a,b). These six innovations were:

- Three types of rotations that are aimed at durably regulating nematode populations: a 12-month fallow chemically controlled to avoid the development of nematode host-plants, an 8-month fallow with *Crotalaria juncea*, and a 24-month rotation with pineapple. We considered that these rotations should be associated with an absence of nematicide treatments during 3 years. These rotations involve additional operations for ploughing, sowing and managing the rotation crop.
- Intercropping the banana with a legume cover crop, *Canavalia ensiformis*. This species is appropriate for banana intercropping as it can limit weed development and provide nitrogen to the soil without increasing the pest populations (McIntyre et al., 2001). This is an annual cover crop that needs regular replanting and mulching at flowering. However, observations of experimental trials showed that it can increase the work duration of other field operations by about 20%.
- A new hybrid cultivar named FB920 that has partial resistance to *Mycosphaerella musicola* and *Mycosphaerella fijiensis* and is sufficiently tolerant to the nematode *Radopholus similis* to avoid fungicide and nematicide application (Tixier et al., 2008b). Whereas this cultivar is less productive (bunch weight 20% lower than classic Cavendish cultivars), it should however allow bananas to be sold at a higher price due to specific commercial characteristics, which are a small size and different taste.
- An innovative organic banana system combining improved fallow with *C. juncea*, intercropping with *C. ensiformis*, new hybrid cultivar, and organic fertilisation, with no use of chemical inputs.

All of these innovations comprise a reduction or total avoidance of pesticides. All the biophysical, technical and economic parameters for describing these innovations were derived from expert knowledge and experiments (Ternisien, 1989; Ternisien and Melin, 1989; Mateille et al., 1994; Chabrier and Queneherve, 2003; Clermont-Dauphin et al., 2004; Queneherve et al., 2006; Motisi et al., 2007; Thammaiah et al., 2007; Tixier et al., 2008b).

2.2.3. Policy and market conditions

The policy and market conditions can be taken into account in BANAD according to two kinds of parameters: the subsidy schemes (agro-environmental contract described by the amount, the modality and the duration of the subsidy), the market output and input prices, and laws aimed at regulating the use of pesticide (e.g., pesticide bans). Regarding the results of the simulation presented later in this paper, the policy and market conditions parameters were those currently observed. However, for innovative management system involving new resistant cultivar that produces a new kind of banana, smaller and with a different taste, we considered the output price of this banana to be 50% higher than that of conventional bananas. For the organic integrated management system, we considered that due to its organic nature, the sale price of banana produced by this system would be 100% higher than that of conventional bananas, which is close to actual price of organic bananas in Europe.

2.2.4. Parameterisation module

In BANAD, the farmer's action on field is modelled by a set of decision rules with decision variables and threshold parameters (Merot et al., 2008). Each operation is described by a set of 11 parameters, presented in Table 2. P1, P3, P4, P5, P10, and P11 are decision variables used to model the farmer's action in the crop management system sub-model. P2, P6, and P7 are input parameters of the biophysical sub-model. P7, P8 and P9 are input parameters of the farming system model and are used to calculate the net income, pesticide use and workload, respectively.

The values of these parameters depend on the scenario that the model user wants to simulate, it means the choice of farm type, innovation and conditions of policy and markets of the simulation. The parameterisation module is aimed at facilitating the definition of these values by allowing the calculation of consistent sets of parameters from the input databases from simple "IF <condition-A = TRUE> THEN <action1> ELSE <action2>" decision rules that are defined by the user. For examples, conditions can be "Farm type = C" or "adoption of improved fallow = TRUE", and actions can be "no more nematicide treatment during the first 3 years after banana plantation". Once the adaptation rules are defined for each innovation, farm type and conditions of policy and markets, the

Table 2
The definitions of the parameters used to describe each operation of the crop management system (CMS).

Parameters	Units	Definition
P1: presence	[a]	Equals 1 if the operation is present in the CMS, 0 otherwise
P2: modality	[a]	Technical modality of the operation
P3: frequency	weeks	Interval between two repetitions of operation
P4: beginning date	Week number	Date from which operations can take place
P5: end date	Week number	Date from which operations cannot be performed any more
P6: amount of pesticides	kg ha^{-1}	Amount of active ingredient applied
P7: amount of chemical fertilisers	kg ha^{-1}	Amount of chemical fertilisers applied (equivalent 15% N, 4% P, 30% K)
P8: amount of non-chemical inputs	€ ha^{-1}	Cost of non-chemical inputs used
P9: operation duration	days ha^{-1} or days plant^{-1}	Duration of the operation
P10: number of the controlling biophysical variable	[a]	Equal to 0 if operation is not controlled by biophysical variables, otherwise gives the number of controlling biophysical variables concerned
P11: activation threshold	[b]	Activation threshold of controlling biophysical variable

[a] Qualitative variable.
[b] Unit depends on the nature of the biophysical variable.

user can easily and rapidly parameterise consistent sets of parameters close to the reality of the farm type and adapted to the innovation assessed. As an example of this adaptation process of the CMS parameters, Table 3 illustrates how the impacts of adopting two types of innovations modify the parameters of the operation "nematicide applications" for farm type A. Adopting a 12-month fallow makes the beginning of the applications switch from week 2 to 210 because, when adopting a 12-month fallow, the model automatically delays the nematicide application by 52 weeks (fallow duration) plus 156 weeks during which nematicide is not required due to the cleansing effect of fallow on the nematode population. The adoption of an organic system de-activates the nematicide application. This case illustrates the effects of integrating intercrops between rows of banana on the duration of this operation (switch from 0.68 days ha^{-1} to 0.81 days ha^{-1}) because the intercrop presence makes all field operations more complex.

2.3. Model components

BANAD is made of two main components, a cropping system model and a farming system model. The cropping system model simulates jointly the biophysical processes and management of the crops occurring on a given type of field of the farm, thanks to two sub-modules interacting: a crop management system model and a crop model. A type of field is defined as a set of fields that are under homogenous pedoclimatic conditions and receive the same technical management at the same time, within a crop rotation.

2.3.1. Crop management system sub-model

This model runs at the field level and at weekly time-step. Its objective is to simulate the operations applied on the field each week. To this end, we first listed all operations that can be made in the fields for all the possible crop rotations of the simulations, for all farm types and all innovations. The length of the simulation depends on the crop rotation considered, depending on the farm type and the innovation that are simulated. Two types of operation are considered. First there are "routine" operations that are made regularly and depend on an objective of frequency. For example, operation "weed management" is generally made every eight weeks in a banana plantation. Second, there are operations that depend on state variables that are calculated by the biophysical model. For example, on a banana plantation, operation "bunches harvest" depends on the number of bunches that can be harvested. To be performed, a certain number of bunches have to be mature. The final output of this sub-model is a matrix that describe the presence or not of all the possible operations for all the weeks of the simulation. A simple algorithm presented in Supplementary material makes it possible to calculate this matrix. This algorithm uses two kind of inputs: (i) the parameters of the decision rules of the crop management and (ii) the values of the biophysical state variables calculated by the crop model and involved in management decisions. Once the matrix of the crop management is calculated, other simple instructions – using parameters P2, P6, P7, P8, and P9 of each operation – make it possible to easily calculate similar matrices which store field performances in terms of workload, cash flows and pesticide use.

2.3.2. The use of the SIMBA model to simulate biophysical processes

The SIMBA crop model (Tixier et al., 2008a) was used in this study to simulate biophysical processes at the field level. This model includes sub-modules that simulate the soil structure, water balance, root nematode populations (Tixier et al., 2006), yield and environmental impacts (Tixier et al., 2007) with a sound balance

Table 3
The values of the 11 operation parameters for the operation "nematicide treatments" for farm type A for the current situation and after integration of two innovations.

Operations parameters	Units	Current management system	Adoption fallow	Adoption organic system
P1: presence	[a]	1	1	0
P2: modality	[a]	Fosthiazate	Fosthiazate	Fosthiazate
P3: frequency	weeks	52	52	52
P4: beginning date	Week number	2	210	193
P5: end date	Week number	260	312	294
P6: amount of pesticides	kg ha^{-1}	3.6	3.6	0
P7: amount of chemical fertilisers	kg ha^{-1}	0	0	0
P8: amount of non-chemical inputs	€ ha^{-1}	0	0	0
P9: operation duration	days ha^{-1} or days plant^{-1}	0.68	0.68	0.81
P10: number of the controlling biophysical variables	[a]	0	0	0
P11: activation threshold	[b]	0	0	0

[a] Qualitative variable.
[b] Unit depends on the nature of the biophysical variable.

between representing the major processes of the system in the region and keeping the model simple to reduce the parameterisation costs in a large range of conditions. SIMBA was chosen because it is well adapted for modelling banana-farming systems, its parameterisation is relatively convivial and its outputs can be automatically compiled in databases, which makes this model easy to link to other models.

It is able to simulate the main specificity of the banana crop, that is, the establishment of an asynchronous flowering regime, which strongly affects the homogeneity of the plant population structure after several production cycles (Tixier et al., 2004). This specificity is important because it influences the work efficiency and dynamics of banana production and therefore the farm functioning. SIMBA makes it possible to account for most of the operations of banana management and for a large set of innovative techniques like rotations, intercropping, new hybrid cultivars, on a large range of farming situations (Blazy et al., 2009b).

2.3.3. Farming system model

The aim of this model is to calculate performances at the farm level. The inputs of this model are the outputs of the cropping system model and the following farm level parameters: farm acreage, crop pattern (nature, order and length of crops), cost of manpower, type and amount of subsidies, banana sale prices and input prices. These parameters are also differentiated by farm types and modified by adoption scenarios (e.g., crop pattern rules are modified by the adoption of new crop rotations) in the parameterisation module.

In the case of banana farms in Guadeloupe, the farms are specialised in banana production for export as this crop represents on average 90% of the productive farmland area (Blazy et al., 2009a). The farm can be represented by a set of semi-perennial asynchronous banana fields producing banana bunches that are harvested weekly and packaged in a conditioning facility unit for export. Several groups of fields have to be considered according to their biophysical characteristics and the date they were planted because the age of banana plants determines their flowering. Thus, any asynchronous flowering calls for different cropping; indeed, many operations are performed on each individual banana flower (e.g., put a plastic bag around the flower to protect it from pests). For example, for a 5-year banana monoculture pattern we have to distinguish five kinds of fields. To model the adoption at the farm level of innovative crop patterns with new crops in rotation with banana, we considered a progressive adoption, which was represented according to a process of transition from one type of rotation to another during which both rotations coexist. This transition was formalised mathematically with transition matrices as proposed by Castellazzi et al. (2008).

Table 4 gives an example of the transition matrix for farm type A currently practicing banana monoculture and adopting a system of banana in rotation with a 24-month pineapple crop. Using the parameters of the decision rules that define the different crop patterns on the farm, the farming system model first simulates the land allocation to the different type of fields of the farm with the method presented above. Then it uses the transition matrices obtained to combine the cropping system performances calculated with the cropping system model into a single farm by calculating the farm level pesticide use, workload, cash flows, and banana production at a weekly step.

For comparing the strategy to adopt an innovative management system versus the status quo situation, we discounted all future cash flows with a discount rate (named R). The discount rate reflects two things, (1) the time value of money (risk rate) that reflects that investors would rather have cash immediately than having to wait and (2) a risk premium rate that reflects the extra return investors demand because they want to be compensated for the risk that the cash flow might not materialise. All future cash flows simulated were then discounted to give their present values with the following formula where DCF is the discounted cash flow and FF is the future cash flow at time (n) expressed in years:

$$\mathrm{DCF} = \mathrm{FF}/(1+\mathrm{R})^n \quad (1)$$

From the discounted cash flows we then calculated with Eq. (1) a total discounted income per year and per hectare for each innovation over the total crop pattern (5 or 7 years in our case). A discount rate of 2.56% was assumed, corresponding to the reference discount rate of French Bank coupons for a 5-year horizon (Banque de France, 2009). We neglected the additional capital cost implications because, except for the adoption of a rotation with pineapple, all the management systems tested do not necessitate a significant investment. Cash flows include work costs, chemical (pesticide, fertiliser) and non-chemical (boxes, plastic bag for bunches, etc.) input costs, subsidy level, and sales of products.

2.4. Software structure

As proposed by van Ittersum et al. (2008), we opted for a framework to link individual models and data components through "plug-in" matrices in which the outputs of one model are the inputs to another one. Three types of software were used in this framework. The first one is the parameterisation tool that has been developed with the Visual Basic Editor®. SIMBA was developed in the STELLA® software version 7.0.2. The crop management system model and the farming system model were developed with the numerical computational package Scilab® version 4.1.2. (Campbell et al., 2006). Although it is composite, requiring the use of three

Table 4
The transition matrix to represent the evolution of land uses at the farm level in the case of a progressive transition from a 5-year monoculture to a 7-year innovative system of rotation, "24-months pineapple/5 years banana", for farm type A.

Years after adoption	Groups of fields of current cropping pattern: banana monoculture					Groups of fields of innovative cropping pattern: 2 years pineapple and 5 years banana							Total acreage (ha)
	BM1-year	BM2-year	BM3-year	BM4-year	BM5-year	P1-year	P2-year	BP1-year	BP2-year	BP3-year	BP4-year	BP5-year	
0	0.84	0.84	0.84	0.84	0.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.20
1	0.00	0.84	0.84	0.84	1.08	0.60	0.00	0.00	0.00	0.00	0.00	0.00	4.20
2	0.00	0.00	0.84	0.84	1.32	0.60	0.60	0.00	0.00	0.00	0.00	0.00	4.20
3	0.00	0.00	0.00	0.84	1.56	0.60	0.60	0.60	0.00	0.00	0.00	0.00	4.20
4	0.00	0.00	0.00	0.00	1.80	0.60	0.60	0.60	0.60	0.00	0.00	0.00	4.20
5	0.00	0.00	0.00	0.00	1.20	0.60	0.60	0.60	0.60	0.60	0.00	0.00	4.20
6	0.00	0.00	0.00	0.00	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.00	4.20
7	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.60	0.60	0.60	0.60	0.60	4.20

Note: Total farm acreage of farm type *A* = 4.2 ha, BM = banana monocrop, *P* = Pineapple, BP = banana after pineapple.

different tools, this software infrastructure provides for the flexible use and linkage of components.

2.5. Model evaluation

To analyse the robustness and the predictive performances of the model, we compared the results of BANAD simulations to the observed values for six types of farms and three performance criteria, which were the banana production, workload, and net income. These three criteria were retained because they reflect both biophysical and technico-economic processes and their interactions. Fig. 2 shows a significant correlation between the simulated and observed values for the banana production at the farm level ($R^2 = 0.93$, $\Pr > F = 0.002$). The linear regression is close to one (1.02), which shows that the predictive performance of the model is correct for banana production. For the workload, the simulated workforce was significantly correlated with the one observed on the six farm types ($R^2 = 0.82$, $\Pr > F = 0.005$). The linear regression is 0.89, which shows that the simulated workload values tend to be about 10% lower than the available observed workforce. The simulation can therefore be considered correct since farmers usually have more resources available than they need, for example to manage possible workload peaks or worker absences.

Table 5 shows the comparison between the farm net income obtained with quantitative simulations and a qualitative indicator provided by farmers through questionnaires (Blazy et al., 2009a). For farm types A, B, C, and E, the model correctly ranks the farm types according to the modal value of income observed in the different group of farms. The model predictions are less satisfying for farm types D and F. This can be explained by the fact that the two groups of farms that have contributed to the elaboration of farm types D and F were more heterogeneous than the others.

The predictive capacity and the robustness of the model was considered satisfying because the model correctly simulates and classifies several performance variables on a wide range of farm

Table 5
The comparisons between the simulated net income and the income indicator provided by farmers for six types of farms.

Farm type	Simulated (k€ ha y)	Farmer's indicator
A	2097	Little income
B	4929	Suitable income
C	−971	Deficit
D	760	Suitable income
E	4850	Suitable income
F	1235	Deficit

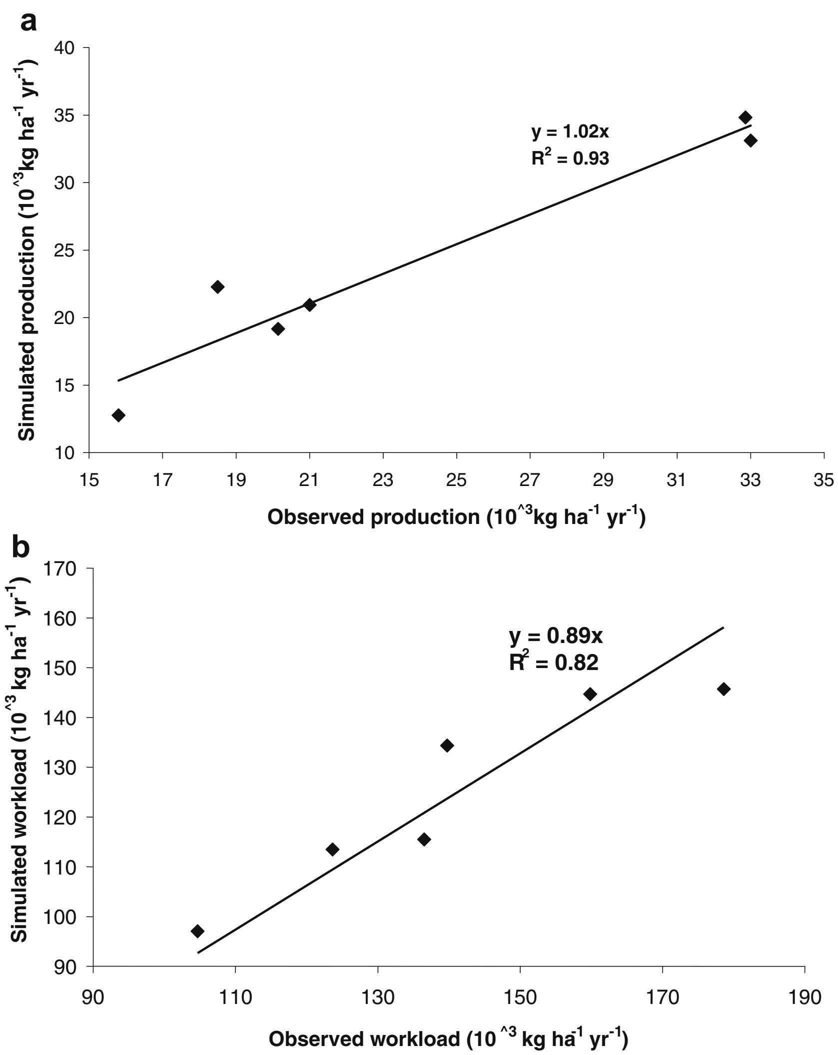

Fig. 2. The comparison between the simulated and observed production (a) and workload (b) for six types of farms.

types that represent contrasted crop management systems and biophysical conditions.

2.6. Setup of the simulations

The aim of the simulations presented in this study was to determine the performance of different innovative banana management systems for the main types of banana farmers in Guadeloupe. We chose to conduct the analysis on farm types A, B and C because these three farm types well describe the diversity of the farming situation in Guadeloupe and are correctly simulated by the model for each type of criteria. However, a focus has been made on farm type A because it represents almost 50% of the total population of banana growers and its current sustainability level is low.

The four types of agro-ecological innovations used in the prototyping of banana systems were tested (Blazy et al., 2009a): intercropping, improved fallow and new crop rotations, hybrid cultivars and an integrated organic system. A previous study at the field level has shown that these innovations could be promising in terms of productivity increases and environmental load decreases (Blazy et al., 2009b). The aim of the study presented in this paper was to test these innovations at the farm level and to assess the economic and technical feasibility of these systems by (i) comparing different agro-ecological innovations on a multi-criteria basis for a given farm type, (ii) assessing the dynamics of impacts at the farm level after the adoption of rotation-based systems, and (iii) assessing the sensitivity of the farm level criteria to innovation parameters and comparing a given innovation among several farm types. We calculated for the three farm types the profitability thresholds of the banana sale prices for the organic management system and the system involving the hybrid cultivars. This threshold was defined as the minimum sale price of banana to make the adoption of this innovative system as profitable as the current system.

3. Results

3.1. Comparison of four innovative crop management systems

In this section we present the dynamic assessment of the impacts of four innovative crop management systems for farm type A. Fig. 3a presents the evolution during the whole crop rotation of the cumulated banana production for five crop management systems implemented: the current system, adoption of a chemically controlled 12-month fallow, adoption of banana intercropping with *C. ensiformis*, adoption of hybrid cultivar FB920, and adoption of organic banana farming (8-month fallow improved with *C. juncea*, banana intercropping with *C. ensiformis*, hybrid cultivar FB920, and organic fertilisation). The impacts of these innovations in production differ with the time-scale used in the analysis. In the long term, the best innovations are the improved fallow and intercropping because they considerably increase the banana production, whereas the hybrid FB920 and organic systems lead to lower production. Although the banana production is increased more by the improved fallow than by intercropping in a long-term level, we observed the reverse in the short term because of the presence of the banana unproductive period in the system involving fallow. The improved fallow is less productive than the current systems during the first 3 years (the curve of improved fallow exceeds that of the current system at about week 160). Conversely, the innovation hybrid FB920 gives a higher production on the short term but is less productive than the current system after week 45. The final yield is indeed clearly lower (about 40% less than the current system). This may be due to the specificities of the yield components of hybrid FB920: the bunches are smaller but the cycle of flowering and maturation is shorter.

The innovations generate higher workloads (see Fig. 3b), except hybrid FB920. Surprisingly, although the improved fallow reduces banana acreage by 20% relative to the current systems, it generates

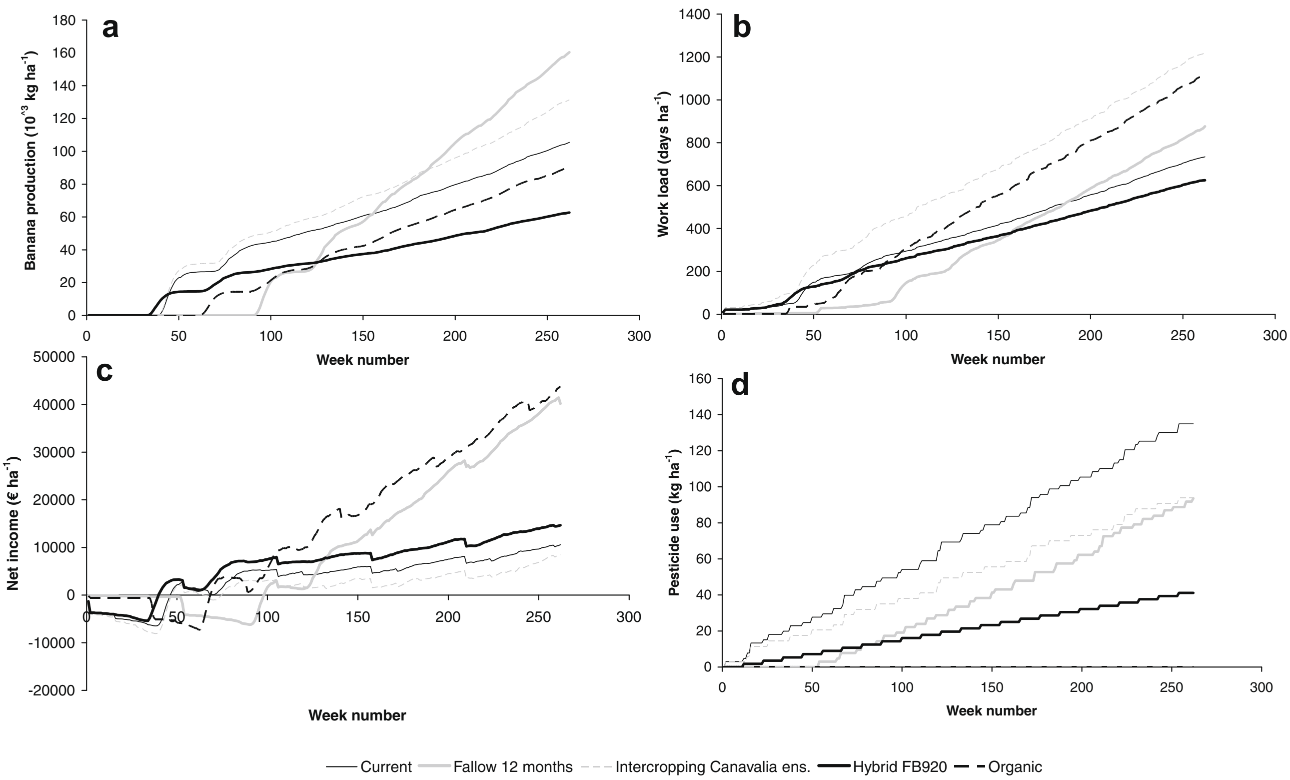

Fig. 3. Simulations of the evolution of the cumulated field performances for farm type A after the integration of four agro-ecological innovations in comparison to the current system. (a) Banana production, (b) workload, (c) net income, and (d) pesticide use.

a greater workload because of its higher productivity. Indeed, increasing the banana production leads to an increased workload for harvesting and conditioning bananas, which represents an increase of between 30% and 50% of the total workload at the farm level in the current situations. At the farm level, this situation corresponds to a switch between field-work to harvesting and conditioning work and thus has a considerable impact on the work management. The inverse is observed for hybrid FB920 because banana production is considerably lower than in the current system, but the workload at the farm level is slightly lower, which corresponds to a decrease in the work for harvesting and conditioning that is almost fully compensated by an increase in field-work. Innovations involving intercropping are particularly work-demanding because, although they result in less production than improved fallow, they need more work for the planting and management of cover crops.

Fig. 3c shows that the adoption of organic and improved fallow systems leads to an increase in the net income. Regarding the organic system, economic results can be explained by the increase of the banana sale price, which largely compensates for the banana production decrease and the considerable workload increase. Nevertheless the sensitivity of the net income to the sale price of organic bananas needs to be further analysed (see Section 3.3). It is interesting to note that, although banana production is considerably reduced by the hybrid FB920, the net income is higher because of the higher sale price than the current system (from 0.558 €/kg to 0.837 €/kg). For this smallholder farm type, the considerable increase in banana production after the adoption of improved fallow provides a much better net income. The situation is different for intercropping, where the increase in banana production does not compensate for the workload increase, which makes the net income with this innovative system lower than that of the current system. The change in total discounted income per year and per hectare over a 5-year period in comparison to the current management system are 5466 € ha^{-1} year^{-1} for the organic integrated system, 4952 € ha^{-1} year^{-1} for the system with 12-months fallow, 351 € ha^{-1} year^{-1} for hybrid cultivar and −680 € ha^{-1} year^{-1} for intercropping banana with *C. ensiformis*. Fig. 3d confirms that all of the innovations reduce pesticide use, by 100% for the organic system and by 70% for hybrid FB920 and approximately 30% for the intercropping and improved fallow systems.

These results show that the adoption of improved fallow seems particularly relevant for smallholders. The following sections focus on the impacts of the adoption of crop rotations and improved fallow for this farm type.

3.2. Assessment of the impacts of the adoption for three types of banana rotations

Fig. 4a presents the evolution of banana production at the farm level for farm type A (acreage = 4.2 ha) after the progressive adoption of three types of rotations, in comparison with the current situation (monocrop): eight months of fallow improved with *C. juncea*, 12 months of chemically controlled fallow, and a 24-month rotation with pineapple. For all rotations, the banana production decreases the first few years after adoption and then increases and considerably exceeds the current situation until the establishment of a plateau. The duration of this lower-production period depends on the crop rotations, i.e., 4.5 years for rotations with pineapple, 2.5 years for fallow improved with *C. juncea*, and 3.0 years for chemically controlled fallow. Then the production increases progressively each year and is stabilised 6 years after the innovation adoption for the two fallows and after 7 years for the rotation with pineapple. The final permanent production level is the highest for the fallow improved with *C. juncea* because the fallow unproductive period is shorter (8 months versus 12 or 24) and because it improves the nitrogen soil content with the biological fixation of this cover crop during the fallow.

The workload at the farm level (Fig. 4b) follows a trend similar to the production, with a decrease the first few years after adoption and then a progressive increase until the establishment of a final stable situation where the workload is clearly higher than in the current situation. The final workload is higher for the improved fallow because of the large increase in banana production, which increases the workload for harvesting and conditioning banana bunches. The system with a pineapple rotation has the same final workload as the chemically controlled fallow although its final banana production level is lower. Note however, that the workload 1 year after the adoption is the same for the rotation with pineapple as in the current system but is then lower up to 4 years after the adoption.

Fig. 4c shows that, although rotations make it possible to increase considerably the net income (from about 9000 € year^{-1} to about 40,000 € year^{-1}), they induce a transition period of 1.5–2.5 years during which the net income decreases drastically the first year after adoption to 3477 € year^{-1} for the improved fallow with *C. juncea*, 6567 € year^{-1} for the chemically controlled fallow, and 2745 € year^{-1} for the rotation with pineapple. However, the rotation with pineapple increases the income level (15,828 € year^{-1}) the second year after adoption due to pineapple sales. The discounted incomes per year and per hectare over a 7-year period are 4507 € ha^{-1} year^{-1} for the 12-month chemically controlled fallow, 4918 € ha^{-1} year^{-1} for the improved fallow with *C. juncea* and 5074 € ha^{-1} year^{-1} for the rotation with pineapple, which confirms the economic relevance of adopting crop rotations for this farm type.

The adoption of these innovations makes it possible to progressively reduce the pesticide use at the farm level (Fig. 4d), from 113 kg year^{-1} to 88 kg year^{-1} for fallow improved with *C. juncea*, 83 kg year^{-1} for chemically controlled fallow, and 76 kg year^{-1} for rotation with pineapple. The latter, however, is above the other rotations the first year after the adoption because of the use of herbicides in the pineapple management systems.

3.3. Assessment of two innovations across three farm types

Table 6 presents the results of the assessment of the innovation “intercropping with legume cover crop *C. ensiformis*” on farm types A, B and C. The impacts of the innovations differ greatly among the farm types. While this innovative management system increases production by 12 to 24% for farm types A and B, it is however not profitable for these farms as the discounted incomes are lower by 680 € and 1483 € ha^{-1} year^{-1}, respectively, compared to the current system. This innovation however increases income for farm type C by 3074 € ha^{-1} year^{-1} in comparison with the current situation. This can be explained by the considerable banana production increase induced by this innovation for farm type C (16 tons ha^{-1} year^{-1}), resulting from the improved nitrogen nutrition of banana plants in a situation where nitrogen stress was probably high in the current system. The current crop management system of this farm type indeed includes only three fertiliser doses per year and is located in a situation where rainfall is abundant, which causes nitrogen losses due to leaching (Dorel et al., 2008). Provided the work increase induced is acceptable, this innovation seems therefore to be appropriate for this farm type.

The profitability thresholds of the banana sale price for the organic management system differ among farm types as follows: 0.737, 1.135, and 0.777 €/kg for farm types A, B, and C, respectively. These differences can be explained by the differences in manpower costs, which are low for farm types A and C and high for farm type B. Indeed, when manpower is expensive, the increase in work will

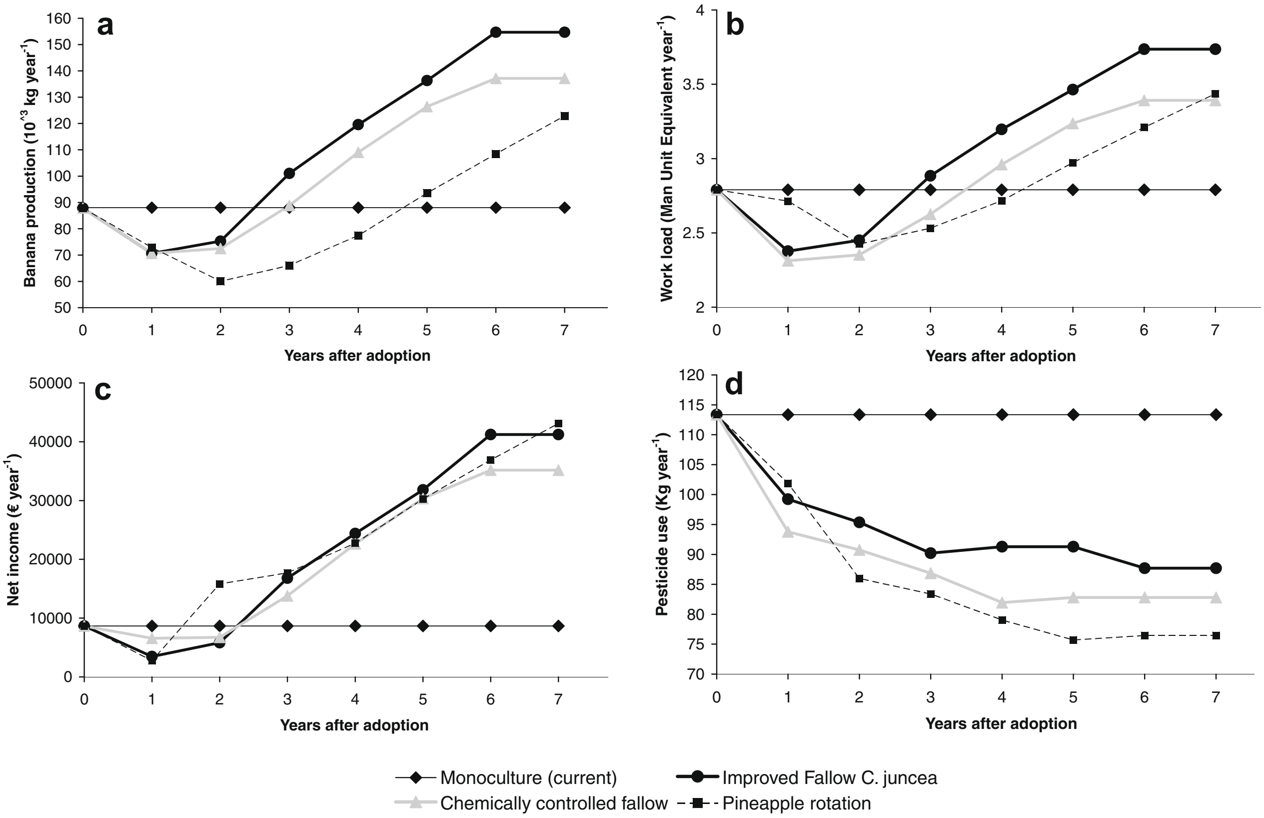

Fig. 4. Simulations of the evolution of the yearly farm performances after the adoption of three innovative crop rotations for farm type A. (a) Banana production, (b) workload, (c) net income, and (d) pesticide use.

Table 6
The absolute impacts of adopting intercropping banana with the legume cover crop *Canavalia ensiformis* in comparison to the current cropping systems for three farm types.

Farm type	Banana production (10^3 kg ha^{-1} year^{-1})	Workload (d ha^{-1} year^{-1})	Total discounted income (€ ha^{-1} year^{-1})	Pesticides (kg ha^{-1} year^{-1})
Type A	**+5** (+24%)	**+96** (+66%)	−**680** (−32%)	−**8** (−30%)
Type B	**+4** (+12%)	**+42** (+37%)	−**1483** (−30%)	−**7** (−23%)
Type C	**+16** (+100%)	**+75** (+77%)	**+3074** (+317%)	**0** (=)

Note: The relative impacts are indicated between brackets.

impact more on the production costs and thus decrease the net income. This confirms that to be economically successful, organic systems need to target specific markets in which the added value of the product can lead to more profitable sale prices.

4. Discussion

4.1. Agronomic and policy recommendations for banana production in Guadeloupe

These results indicate several agronomic and policy recommendations for improving the likelihood of the adoption of agro-ecological innovations in banana-farming systems of Guadeloupe. First, we identified which innovations would be relevant for farm type A, which represents smallholders that constitute about 50% of the total population of growers. Our study provides contrasting results. The adoption of fallow seems to be relevant for this farm type because it induced an increase in production after 3 years and an increase in income after 2.5 years. However, it induced a strong decrease in the farm income during the first 2.5 years and this transition period can be a key constraint to adoption for smallholders, as observed in other studies (Lojka et al., 2008). The adoption of a cash crop rotation (pineapple) could reduce this transition period from 2.5 to 1.5 years, but it would induce a stronger decrease in the net income in the first year. One solution would be to provide smallholders access to credit to maintain their vital income during this critical period or to give them a subsidy for conversion during the 3 years following adoption.

Innovations based on intercropping with legumes are suitable for farm type C, whereas for farm types A and B, adopting this innovation can lead to an erosion of income. This loss of income is due to a workload increase, which is generally the case for conversion to low-input systems as they are assumed to substitute chemical inputs with other factors such as management knowledge, labour or land (Padel and Lampkin, 1994). Incentives to promote the adoption of this innovation for banana growers in Guadeloupe should include financial compensation from about 700 € ha^{-1} year^{-1} to 1500 € ha^{-1} year^{-1} for farm types A and B, respectively.

New hybrid cultivars are interesting from an environmental point of view as they strongly decrease the pesticide use (−70%), but they are not productive enough to make the innovative CMS profitable. Breeders will have to focus on increasing the bunch size and the cycle length and decreasing the height of bananas to make this innovation more economically attractive. Even though combining this innovation with intercropping, improved fallow and organic fertilisation would increase the CMS productivity and avoid pesticide use, it should nevertheless be accompanied by a substantial increase in the sale price from about 0.56 €/kg to at least 0.78 €/kg for farm types A and C and 1.14 €/kg for farm type B, to maintain the current level of farm income. Consumer willingness to pay for such environmentally friendly products should therefore be investigated to assess more precisely the economic potential of this innovation. This could be done with choice experiments and econometric models (Langyintuo et al., 2005). In the current situation, these organic systems seem more relevant for smallholders for whom manpower is mainly familial, cheap and abundant.

4.2. Model limits and effectiveness

One of the limits of our study is that, although we considered specific and differentiated climate datasets for each farm type, we considered an average climatic year. The sensibility of innovation performances to contrasted climatic seasons needs to be evaluated. To analyse this sensibility, complementary simulations with extreme climatic datasets should be further performed. Another limit is that we have not focused on management planning constraints. Based on the concept of "farmer's action model", some authors have provided interesting approaches to identify planning constraints (Joannon et al., 2005; Dounias et al., 2002). We could take into account such kind of constraints by integrating one or several additional planning constraints in the core algorithm of the crop management system model.

Thanks to BANAD, we could rapidly identify in a wide range of real conditions of farms the critical factors or periods associated with the adoption of agro-ecological innovations, and the economic, biophysical, and technical conditions under which each innovation is relevant. As discussed in Section 4.1, these factors have to be therefore considered in the prototyping systems research program to orient the design of the innovative crop management systems toward more high-performing and efficient systems. Our results applied to several kinds of agro-ecological innovations and different farm types of Guadeloupe have confirmed that impacts of innovations are indeed ambivalent according to the farm type, the criteria and the temporal horizon of the analysis that are considered in the assessment. Such assessments studies would be almost impossible to do with on-farm trials but is much more easy and quick with computer models like BANAD. Such trials are nevertheless now required to validate our results. The advantage of our approach is that it allows one to identify the most promising "innovations by farm types" situations to be assessed – and so to reduce experimentation costs – and to precisely adapt the features of the innovations to make them more efficient and consistent with farms conditions.

Although BANAD has been initially developed for banana farms, its generic component structure and the simple mathematic formalisms used to model cropping and farming systems could be used in other contexts. Applying such modelling in other contexts would be easy and rapid if one has expert knowledge and data on crops and on farms, a frequent situation when current systems are well established but no longer durable. The BANAD model can be used as a stand-alone version but it would be relevant to integrate it into a more complex framework accounting for different spatial levels and in which strategic decisions of farmers are modelled, e.g., like in the Seamless platform (van Ittersum et al., 2008). This would allow to help in the calibration of policy schemes to promote the adoption of environmentally friendly innovations. Such integrated modelling approaches could open new areas of research in which the innovations and the policies can be co-assessed and co-designed on the basis of multi-criteria mechanistic assessments. The contribution of BANAD to this kind of research is that it allows the precise assessment of the potential operational impacts of innovation adoption. These impacts can then be used for describing innovation attributes that would then be input parameters of optimisation or random utility econometric models that explicitly model the strategic decision of adoption (Torkamani, 2005; Lapar and Ehui, 2004).

5. Conclusions

We developed a simple mechanistic dynamic farm model to assess *ex ante* the impacts of several agro-ecological innovations on different farm types. The results obtained from the application of the method to banana growers in Guadeloupe showed that the adoption of rotations can be problematic during a transition period following adoption, which considerably reduces the farm level income for smallholders. The adoption of new hybrids and organic systems reduces considerably the pesticide use, as well as the productivity, but it can be profitable under different marketing scenarios. Intercropping with a legume cover crop like *C. ensiformis* is interesting for its capability to reduce herbicide use while increasing the cropping system productivity, but its profitability is lowered by the increased workload. However, this innovation can be efficient on all criteria for a farm type. The assessment of several innovations for a farm type showed that, according to the assessment criteria and the time-scale of the analysis, the results can differ and the impacts can be ambivalent. This confirms the need to consider factors often neglected in *ex ante* assessment studies like (i) the interactions between the farm types and innovations, (ii) the need to consider at the same time the economic, environmental and agronomic consequences of adoption, and (iii) the importance of dynamics in modelling the performances of innovations at the farm level, in particular for innovative crop rotations. Compared to on-farm trials, BANAD makes this kind of assessment possible quickly and with fewer resources provided it is applied in a regional situation where the farms and crops are well characterised. This kind of modelling approach can therefore be useful to facilitate the formulation of strategic orientations for agronomic innovation research and policy definitions. We believe that the methodology and the formalisms proposed to build BANAD are relatively generic and should be useful to other modellers and prototyping scientists, in particular for building integrated modelling frameworks in which innovation and policy are co-assessed.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agsy.2010.01.004.

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