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SIMBA, a model for designing sustainable banana-based cropping systems

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Abstract

Banana monocultures (*Musa* spp., AAA, Cavendish sub-group cv. Grande Naine) can have a detrimental impact on the environment. In these agro-systems, pesticide treatments can lead to surface and groundwater pollution, as is the case in the tropical insular conditions of the French West Indies. Using models to design alternative cropping systems is of growing interest but most of the research work has been concentrated on annual crops and most often in temperate climate. A specific model called SIMBA was built to assess environmental risks under a large range of cropping techniques and to help design more sustainable cropping systems. 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 phenomena well and keeping the model simple to reduce the parameterization costs in a large range of conditions. Agro-environmental indicators generated by the model make it possible to assess the major potential environmental impacts. The model has been developed and calibrated in Guadeloupe and Martinique and is used to draw up practical recommendations for farmers and for virtual experiments of agro-technological innovations or field management strategies. The structure of SIMBA is presented and a methodology is proposed for designing sustainable banana-based cropping systems using the model. SIMBA has been evaluated in a broad range of cropping systems in Guadeloupe by comparing model estimates to data collected in field experiments and surveys. Simulations lead to trends in rotation-based cropping systems characterized by systems that can be considered as intensive for profit evaluation, and combinations of frequent replanting, low nematicide application, no ploughing, and low fertilization level, for environmental evaluation. Simulations performed to optimize the replanting decision rule showed that relatively frequent replanting is good for profit while low frequency replantations (over four banana cycles) give a better environmental evaluation.

Keywords: Crop model; Agro-environmental indicators; Multicriteria evaluation; Guadeloupe; *Musa* spp.

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1. Introduction

Intensive agriculture has led to major environmental issues that affect global sustainability (Tilman et al., 2002). It is now essential to design new cropping systems to address both the needs of farmers, the authorities, and the society, while preserving the environment simultaneously. Several strategies are being explored to solve these problems, including new field practices or new spatio-temporal arrangements of practices. New concepts

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and innovative predictive tools are needed to design more sustainable cropping systems (Boiffin et al., 2001). Agronomists must work in multidisciplinary research groups that include modelers, social scientists, and plant pathologists in collaboration with farmers′ groups (Boiffin et al., 2001; Meynard et al., 2002; Dogliotti et al., 2004). Vereijken (1997) proposed a methodology for designing farming systems involving four steps, respectively: (i) analysis and diagnosis, (ii) design, (iii) testing and improving, and (iv) dissemination of a prototype (Sterk et al., 2007). Designing a prototype always begins with a thorough survey of the situation and an assessment of potential developments. This analysis facilitates the choice of the most appropriate model outputs or the additional complementary analyses and experiments that are required. Dogliotti et al. (2004) proposed that this approach can be improved by models, which allow fast exploration of crops and techniques and can be used to optimize their combinations and evaluate their production and externalities. Another type of model-based approach has been used to design prototypes of wheat-based cropping systems (Loyce et al., 2002a,b). This model simulates and compares specified cropping systems on the basis of their yield, cost, gross margin, nitrogen use, pesticide use, seed quality, and energy balance. When targeting sustainability in the evaluation of cropping systems, one needs to consider both an environmental objective defined by society or the authorities and an economic objective defined by the farmer. In this context, scientists or stakeholders have to set objectives, which are often a trade-off between environmental and economic constraints. However, most crop models perform evaluations simply on the basis of a few criteria, such as yield, and may not take into account the effects of all innovative techniques, which limits their utilization to design prototypes (Lançon et al., 2007).

In the case of banana-based cropping systems, evaluations have to focus on agronomic performances as well as environmental impacts, i.e. mostly risks linked with pesticide dissemination in the environment. Throughout the world, banana production (*Musa* spp., AAA, Cavendish sub-group cv. Grande Naine) for export is mainly based on intensive monocrop systems, which are generally not environmentally friendly. The agronomic and ecological sustainability of these systems is often hampered by a high level of root parasitism, including nematodes. Air, soil, and water quality may be adversely affected by the frequent applications of chemical pesticides that are required to control this 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 close to agro-systems (Bonan and Prime, 2001; Bocquené and Franco, 2005). This issue also concerns all areas of intensive production of banana (Matthews et al., 2003; Castillo et al., 2006; Chaves et al., 2007). At the same time, managing manpower, adapting to a fluctuating and highly competitive market, or limiting pesticide use are major economic problems that threaten the whole banana production sector in F.W.I. (Bonin et al., 2004).

To design new banana-based cropping systems, a model called SIMBA was built to simulate this system and to assess its performances and impacts. The model takes into account the specificities of this semi-perennial tropical system and seeks to simulate the set of outputs needed to assess its performances on a multicriteria basis. To fulfill these objectives, biophysical modules were developed and a set of economic and environmental indicators were defined. SIMBA can be used to optimize suitable practices that take into account the dynamics of the state variables of the system (pests, plant population, soils, etc.) in order to reach a target objective. The design of the model was therefore mainly driven by a pull approach guided by the cropping techniques (generated as much as possible by decision rules) and by the assessment criteria. Knowledge on the key biophysical mechanisms was available from experiments and experts' knowledge, which served to build a modular soil-crop-nematodes model linking techniques and indicators. SIMBA was developed to simulate and assess the main environmental risks in banana-cropping systems (pollution of water and soil erosion) over several cropping cycles.

In this article, we present how a model like SIMBA could be used to evaluate existing or innovative cropping systems in a variety of soil and climate situations and thus helps select the best cropping system prototypes for on-farm experiments. We first present the structure of the SIMBA model, and then we present a two-step method to generate and assess cropping systems with the model. The example of banana-fallow rotations is explored and optimized regarding economic and environmental goals.

2. The SIMBA model

2.1. Model structure

Instead of starting from an existing crop model, adapting it to the banana-nematodes system, and deriving some indicators from the output variables, we created a new model to produce the assessment indicators based on existing knowledge. This modelling approach allows accounting for the specificities of the system and to use expert knowledge more easily. The evaluation criteria of the simulated systems were profit margin and environmental risks associated to pesticides and erosion. Consequently, the yield and the state variables of the system, and their dynamics, have to be taken into account. Two types of formalisms were developed to compute these variables. For processes that can be simulated biophysically, process-based modules were developed. These included plant growth, plant population structure, soil cover, physical soil properties, water balance, and plant-parasitic nematode population densities. For processes that cannot be easily simulated at field level, semi-qualitative indicators based on expert systems and fuzzy logic were developed, using some of the outputs of the biophysical modules. The biophysical system is driven by a technical system (as defined by Rapidel et al., 2006) that can be generated by decision rules or forced by the user. The general structure of SIMBA includes interactions between modules (Fig. 1).

SIMBA and all its modules run at a weekly time-step at the field scale. All modules were calibrated using data previously collected in F.W.I. A detailed description of SIMBA can be found in Tixier (2004) and the most innovative modules are presented in Tixier et al., 2004a, 2006). SIMBA has been developed in the STELLA® software version 7.0.2 from Isee systems (formerly High Performance System®). STELLA is a modeling tool for building a dynamic modeling system by creating a pictorial diagram of a system and then assigning the appropriate values and mathematical functions to the system (Isee Systems, 2007). The key features of STELLA consist of the following four tools:

- stocks, which are the state variables for accumulations; they collect whatever flows into and out of them,
- flows, which are the exchange variables and control the arrival or the exchanges of information between the state variables,
- converters, which are the auxiliary variables; these variables can be represented by constant values or by values depending on other variables, curves or functions of various categories,
- connectors, which are used to connect modeling features, variables, and elements.

Modules interact with climate and farmers′ practices via decision-rule processes. Crop models, such as CROPSYST (Stöckle et al., 2003), STICS (Brisson et al., 1998), DSSAT (Jones et al., 2003), and APSIM (Keating et al., 2003), use inflexible and not interactive calendars to describe agronomic practices. Other approaches optimize decision rules with models, e.g. fertilization decision rules (Makowski and Wallach, 2001) or irrigation decision rules (Bergez et al., 2002). 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 as proposed by Aubry et al. (1998). For example the quantity of

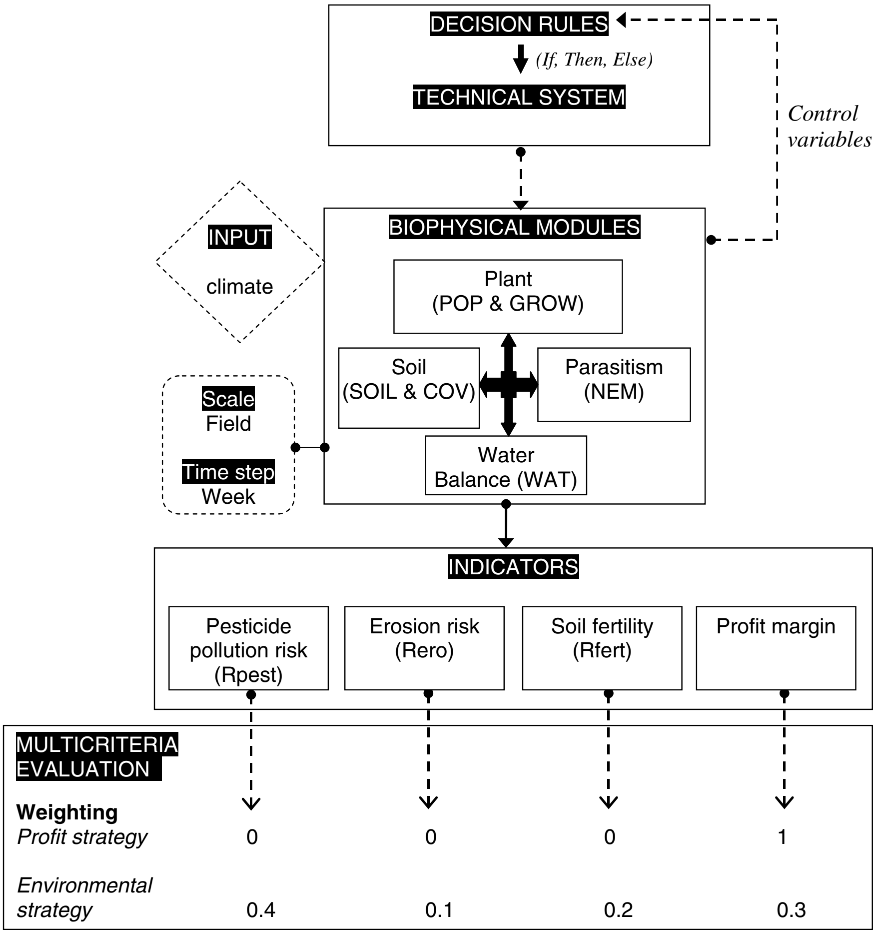

Fig. 1. Diagram of the SIMBA simulation framework with decision rules that describe the tested technical system and the biophysical engine simulation that includes plant population (POP), plant growth (GROW), plant-parasitic nematode dynamics (NEM), soil structure (SOIL), soil cover (COV), and water balance (WAT) modules, leading to indicators used for the multicriteria evaluation.

nematicide applied per week is determined by the nematode density or by the number of weeks since the last application (Fig. 2). These algorithms take into account tactical decision rules applied to the weekly state variables of a banana-cropping system and strategic decision rules applied to the structure of the system. Tactical decision rules apply to fertilization, pesticide application, soil management, plant protection, and plant population management. Strategic decision rules apply to banana replanting and rotations with other crops. These rules are presented in Table 1. SIMBA may also be used to assess existing cropping system through a control panel to describe a pre-defined technical system (Tixier et al., 2004b). The frequency of replanting the banana field is a key decision rule of the management of the nematode parasitism. Indeed, replanting after a fallow or a rotation strongly reduce the nematode populations,

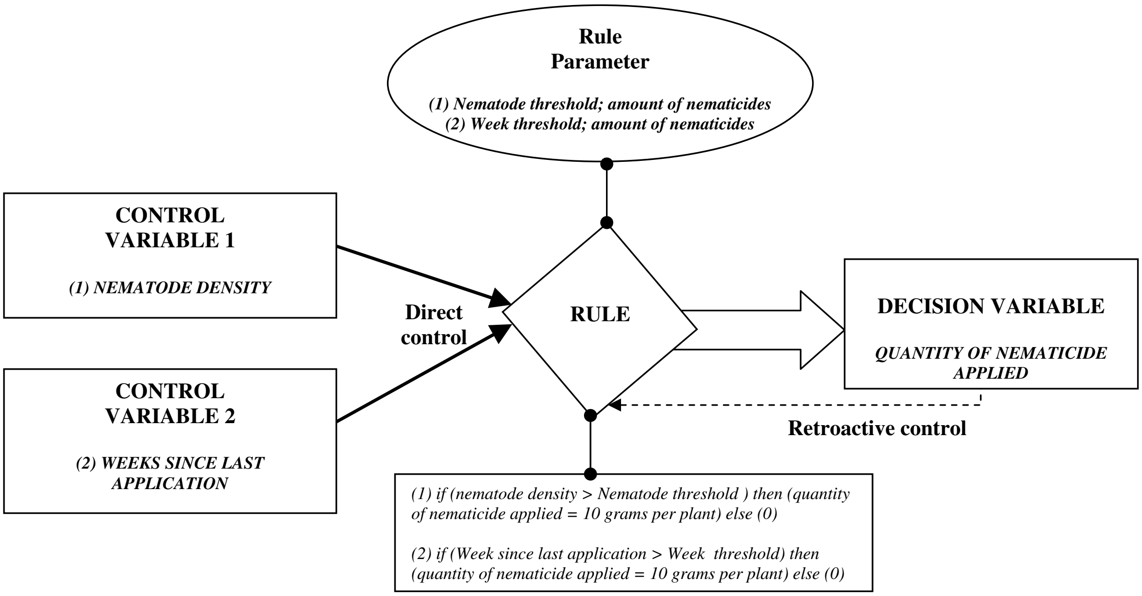

Fig. 2. Structure of a decision rule and its associated control, decision variables, and rule parameters, and an example of decision rules for the nematicide application (in italics).

Table 1
Tactical and strategic decision rules and associated decision and control variables used in the simulations

Phenomenon	Decision variable	Control variable nature	Units	Range	Nbr. of variants
Tactical decision rules					
Nematode control	Nematicide application (g w^{-1} plant^{-1})	**1. Time since last application**	**Weeks**	**10–100**	**10**
		2. Percentage of fallen plants	%	0–100	10
		3. Nematode density per roots	Nbr. g^{-1}	20–200	10
Fertilization	Frequency and amount of nitrogen (g w^{-1} plant^{-1})	1. Time since last application	Weeks	2–10	5
		2. Forced value of fertilization level (1: 80 g/8w, 2: 100 g/5w, 3: 130 g/3w)	–	**1–3**	**3**
Plant population management	Plant bracing and replacement	1. Percentage of fallen plants	%	0–100	10
		2. Forced replacement threshold	**%**	**0–0.30**	**3**
Mechanization And ploughing	**Mechanization of practices** and ploughing	**1. Soil compaction score**	**Note/10**	**0–10**	**11**
		2. Forced values of mechanization (1: none, 2: ploughing only, 3: all activities)	–	**1–3**	**3**
Strategic decision rules					
Planting banana in monocultures	Activate replanting of banana	**1. Number of cycles**	–	**1–15**	**15**
		2. Last cycle yield	kg cycle^{-1}	45–10	8
Rotation with sugarcane or fallows	Activate end of banana	**1. Number of cycles**	–	**1–15**	**15**
		2. Last cycle yield	kg cycle^{-1}	45–10	8

The control variables in bold are the one used in the exhaustive exploration.

leading to an optimal growth of plant and to few or zero nematicide application during two to four cropping cycles. Nevertheless, the cost of replanting and of the unproductive period during the fallow has to be considered in the economical performances.

The validation of the whole model, including all interactions between modules, is complex. This is mostly due to the high number of inputs (parameters and data) and outputs. In this context, numerical validation is almost impossible because of the large volume of data that would have to be collected. As a result, each module has been numerically validated separately, using external data from Guadeloupe. Table 2 presents the evaluation of individual modules. However, this validation of the different modules does not ensure the validation of interactions between modules (Wallach and Goffinet, 1989). On the other hand, SIMBA aims only at sorting cropping systems on the basis of their economic, agronomic, and environmental characteristics in order to identify a limited number of cropping systems for further field experiments. Meanings and units of variables detailed in modules′ description are presented in Table 3.

2.2. Biophysical modules

2.2.1. The plant population module SIMBA-POP

Bananas are rhizomatous herbs whose terminal bud produces the inflorescence. Each plant successively produces suckers issued from a lateral shoot. The sequence can be repeated for 1–50 generations or more, which means that it can be considered as perennial (Turner, 1994). Thus, long-term simulation is essential for assessing banana-cropping systems. In a banana field, each plant develops at its own rhythm, and the plant population does not follow a synchronous cycle. The initially homogeneous plant population becomes heterogeneous after few cropping cycles, i.e. plants in the field can be at different phenological stages at the same time. This process has a central influence on crop yield and on water and nitrogen balances, soil cover, and pest dynamics. The SIMBA-POP module (Tixier et al., 2004a), based on the cohort population concept, simulates the plant population structure and its development patterns, including the management of the plant population by the farmer (choice of sucker for next cropping cycle, plant toppling and replacement).

Table 3
Meanings and units of variables of SIMBA-GROW, SIMBA-COV, SIMBA-SOIL, SIMBA-WAT, and SIMBA-ECO

Variable	Meaning	Unit
SIMBA-GROW		
NF(i)	Number of fruits of cohort I	Nbr.
LAI(i,t)	Leaf area index of cohort ‘i’ at step ‘t’	$m^2 m^{-2}$
NPP(i,t)	Weekly net primary production of cohort ‘i’	$kg\ m^{-2}\ week^{-1}$
LP	Percentage of leaves among vegetative organs	%
SLA	Leaf surface produced by dry matter unit	$m^2 kg^{-1}$
LAImax	Maximum LAI of the canopy	$m^2 m^{-2}$
DLAIP(t)	Variation of LAI the cohort ‘i’ at step ‘t’	$m^2 m^{-2}$
LAIP(i,t)	LAI production of the cohort ‘i’ at step ‘t’	$m^2 m^{-2}$
LUE	Light-use efficiency	$kg\ MJ^{-1}$
$I_{PAR}(i,t)$	Crop-intercepted photosynthetically active radiation of the cohort ‘i’ at step ‘t’	$MJ^{-1} m^{-2}\ week^{-1}$
GSF(i,t)	Growth stress factor of the cohort ‘i’ at step ‘t’	–
mla	Maximum leaf age	weeks
SIMBA-COV		
COV(t)	The total percentage of soil cover (weeds and crop residues) at step ‘t’	%
WG(t)	The percentage of soil cover by weeds at step ‘t’	%
RES(t)	The residues of the banana crop at step ‘t’	%
RD(t)	The crop residue degradation at step ‘t’	%
SIMBA-SOIL		
COMP(t)	The compaction score at step t	note/10
NM(t)	The number of mechanized passages at step t	note/10
SW(t)	The soil water content correction factor on the compaction (reduced if low)	note/10
NP(t)	The number of ploughings at step t	note/10
CE	The compaction effect of each mechanized passage	note/10
DE	The decomposition effect of each ploughing passage	note/10
SIMBA-WAT		
Kro(t)	The run-off at step ‘t’	mm
Kropot	The potential run-off for a given soil type	%
Krocov(t)	The correction factors due to soil cover	–
Krocomp(t)	The correction factors due to soil structure	–
SIMBA-ECO		
GM	The gross margin over the simulation	€
BW(t)	The banana fruit weight harvested in week ‘t’	$kg\ week^{-1}$
SP(t)	The selling price per kilogram of banana in week ‘t’	$€\ kg^{-1}$
MC(t)	The manpower cost at step ‘t’	€
IC(t)	The input cost at step ‘t’	€

Table 2
Separate validation of SIMBA modules, with the correlation factor (R^2) or the normalized root mean square error (RMSE) between the measured and the simulated variables

Module	Simulated variable	Evaluation	Number of data	Origin of data
SIMBA-POP	Date of harvesting peaks	$R^2 = 0.99$	29	Tixier et al. (2004)
SIMBA-GROW	Yield (per year)	$R^2 = 0.55$	12	See Fig. 3
		RMSE = 26.3	12	See Fig. 3
SIMBA-NEM	Nematodes population (week-1)	RMSE = 62.0	63	Tixier et al. (2006)
SIMBA-WAT	Water potential (week-1)	RMSE = 20.6	41	Tixier, unpublished data
Rpest	Pesticide risk rank	$R^2 = 0.92$	5	Tixier et al. (2007a)

2.2.2. The plant growth module SIMBA-GROW

In the Growth module (SIMBA-GROW), plant growth is calculated separately for each cohort defined in SIMBA-POP module. This allows calculating separately the growth of each group of plants at the same physiological stage. This module includes simulation of leaf area index (LAI), vegetative dry matter (leaves, pseudo-stem, roots), and yield (number and weight of fruits per bunch). The number of fruits (NF) per bunch is assumed to be a function of the LAI at the flowering stage, using data of Jannoyer (1995) as presented in Eq. (1). Biotic and abiotic stresses are simulated; these reduce the growth potential due to the impact of nitrogen shortage, drought, or parasitism. As in many crop models, the net primary production (NPP) and LAI are calculated on the basis of the interception of the photosynthetically active radiation (PAR) and its allocation to different organs according to the stage of the plant. During the vegetative period, the net primary production (Eq. (2)) is allocated to vegetative organs, including leaves, which permits the leaf area index (LAI) to be calculated (Eqs. (3) and (4)). During the reproductive period, NPP(i,t) is allocated to reproductive organs (fruits), and the LAI only decreases by senescence. The growth stress factor is calculated using outputs of other modules; it integrates nematode populations and the Rfert indicator (see below).

$$\mathrm{NF}(i) = 28 \cdot \mathrm{LAI}(\text{flowering stage}) + 69 \tag{1}$$

$$\mathrm{NPP}(i,t) = \mathrm{LUE} \cdot I_{\mathrm{PAR}}(i,t) \cdot \mathrm{GSF}(i,t) \tag{2}$$

$$\mathrm{DLAIP}(i,t) = \mathrm{NPP}(i,t) \cdot \mathrm{LP} \cdot \mathrm{SLA} \cdot \left(\frac{\mathrm{LAImax} - \mathrm{LAI}(i-1,t-1)}{\mathrm{LAImax}}\right) \tag{3}$$

$$\mathrm{LAIP}(i,t) = \mathrm{LAI}(i-1,t-1) + \mathrm{DLAI}(i,t) - \mathrm{DLAI}(i-\mathrm{mla},t-\mathrm{mla}) \tag{4}$$

(details on variables are given in Table 3).

This module has been calibrated using data from Guadeloupe (Jannoyer, 1995; Dorel, 2001). SIMBA-GROW simulates yield expressed in $\mathrm{Mg\,ha^{-1}\,year^{-1}}$ and in $\mathrm{Mg\,ha^{-1}}$ cropping cycle^{-1}. Using independent data (e.g. not used for calibration) of a field survey in Guadeloupe in 2000 (Tixier, unpublished data) we obtained a R^2 correlation coefficient of 0.72 between measured and simulated yields (Fig. 3). The RMSE is equal to 26.3% which can be considered as a low predictive accuracy, but that is compatible with the comparison of cropping systems within a wide range; from the most extensive to the most intensive. This survey was performed at the field scale on 12 farms, within a wide range of soil and climate conditions representing the major types of banana-cropping systems in Guadeloupe. It includes a precise description of the cropping system with the crops in rotation with banana, the plant population management, the fertilization and pesticide program, the description of the mechanization practices, the manpower used, and an evaluation of the yield based on the number and the mean weight of fruit per bunch, and the interval between two harvesting cycles.

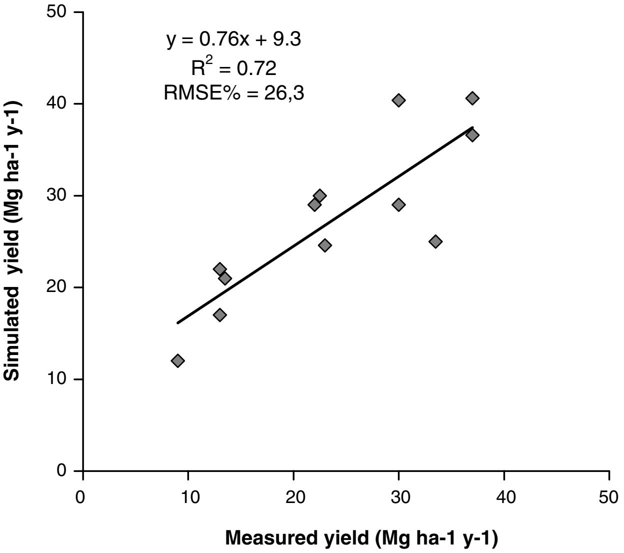

Fig. 3. Measured and simulated yield with the SIMBA-GROW module for 12 cropping systems based on their precise technical description and evaluation of the yield (Tixier, unpublished data). Simulations were performed on the basis of the technical description and soil and climate of each situation.

2.2.3. The plant-parasitic nematode population module SIMBA-NEM

Radopholus similis and *Pratylenchus coffeae* are plant-parasitic nematodes that generate extensive root lesions and that are considered among the most detrimental pathogens of banana. The SIMBA-NEM module (Tixier et al., 2006) is based on a cohort chain structure and a logistic function to describe population growth in relation with (i) '*K*' the environmental carrying capacity (maximal population that the system can support) depending on the available banana root dry matter, (ii) '*c*', an intrinsic growth rate, and (iii) the interspecific nematodes competition. Soil water content and nematicide applications are considered the main variables influencing the intrinsic population growth rate of each species. The model was calibrated with a large dataset representing the major types of banana crops in Guadeloupe (Tixier et al., 2006) and was therefore considered valid for the conditions simulated in this paper. This module takes into account different initial situations of nematode populations, such as after fallow (Chabrier and Quénéhervé, 2003) or after sugarcane. SIMBA-NEM simulates the nematode population with a RMSE values equal or less than 25% of the maximum observed values. It can be considered as a low accuracy, but this precision is enough to help the nematode population management because it allows determining the periods of low population, exponential growth or high population (Tixier et al., 2006). Outputs of SIMBA-NEM are used to calculate the growth and development stresses using the mean value of *R. similis* population over the last 40 weeks (the average duration of a banana cycle).

2.2.4. The soil properties modules SIMBA-COV and SIMBA-SOIL

Soil cover and soil compaction are simulated by the semi-quantitative SIMBA-COV module (Tixier, 2004). Soil cover represents, in a simplified way, the growth of weeds, their destruction by herbicide, the mulch cover supplied by weed destruction and crop residues at harvest of banana, and the mulch degradation over time; it runs at the week step. Weed growth follows a logistic function and is expressed in percentage of soil cover; this growth is reduced when the LAI of the banana increase. Crop residues (in Mg) are converted into percentages of soil cover. The calibration was done using data from Guadeloupe collected during a field survey in 2000 (Tixier, unpublished data). The percentage of soil cover is calculated in Eq. (5). It includes the weed growth calculated with a simple growth module, the residues of the banana crop calculated with the SIMBA-GROW module, weed control with herbicide, and the crop residue degradation as a function of time.

$$\mathrm{COV}(t) = \mathrm{COV}(t-1) + \mathrm{WG}(t) + \mathrm{RES}(t) - \mathrm{RD}(t) \tag{5}$$

(details on variables are given in Table 3).

Soil structure is simulated with the SIMBA-SOIL module through a compaction score (Eq. (6)) that takes into account the number and the type of mechanized practices (fertilizer application, harvest trailer, plowing). The effect of these practices is also affected by soil moisture. This module has been calibrated using data of Dorel (2001) that measured on soil profiles the percentage of every soil structural type with different levels of compaction for a wide range of cropping systems at different stages and after planting.

$$\begin{aligned}\mathrm{COMP}(t) = \mathrm{COMP}(t-1) &+ [\mathrm{NM}(t)\cdot \mathrm{CE}\cdot \mathrm{SW}(t)]\\ &- [\mathrm{NP}(t)\cdot \mathrm{DE}]\end{aligned} \tag{6}$$

(details on variables are given in Table 3).

2.2.5. SIMBA-WAT

SIMBA-WAT is a simple water balance module used to simulate the soil water content, run-off, and leaching. The soil is considered as a reservoir supplied by rainfall, decreased by crop evapotranspiration (according to the simplified Penman equation based on the global radiation and a crop factor calculated as a function of the LAI; FAO, 1998); a run-off coefficient (Kro(t)) is calculated according to soil properties (Eq. (7)). It includes the potential run-off for a given soil type, e.g. 7% for andosol of Guadeloupe. The correction factors due to soil cover is a linear function, equals to 0 for a cover of 100% and equals to 1 for a nil cover. The correction factors due to soil structure is a linear function equals to 0.3 for a nil compaction note and equals to 1 for the maximal compaction note of 10.

$$\mathrm{Kro}_{(t)} = \mathrm{Kropot}\cdot \mathrm{Krocov}(t)\cdot \mathrm{Krocomp}(t) \tag{7}$$

(details on variables are given in Table 3).

Leaching is the last term of the water balance. This module was designed to take into account the soil and climate conditions of Guadeloupe (volcanic soils, high rainfall) (Tixier, 2004). Soil depth considered in SIMBA-WAT is the soil layer potentially explored by banana roots. It was calibrated using datasets obtained in experimental fields where rain, run-off, and water potential in soil were measured during 12 months and using the results of Khamsouk (2001). One limit of the SIMBA-WAT module is that intensity of rains is not considered and it only account for weekly rainfall. Nevertheless, SIMBA-WAT was evaluated with data from Guadeloupe; the potential of water in soil was simulated with a normalized RMSE equals to 20.6%, which can be considered as a low predictive accuracy, it is nevertheless compatible with agronomic management (Table 2).

2.3. Indicators and multicriteria evaluation

2.3.1. The gross margin module SIMBA-ECO

The SIMBA-ECO module calculates the gross margin (Eq. (8)) on the basis of the cost of manpower and agricultural inputs (fertilizer, pesticides, etc.) and on incomes due to the sale of bananas. The manpower is counted for every application of a technique (pesticide application, harvesting, etc.). Income is calculated weekly using banana yields and the sale price of banana for the considered week. The sale price varies throughout the year (Loeillet, 2005; ODM, 2005). Manpower time and input cost associated with every field practice were calibrated using data of Manceron (2004).

$$\mathrm{GM} = \sum\nolimits^{(t=1\ \text{to}\ t=n)}[(\mathrm{BW}(t)\cdot \mathrm{SP}(t)) - \mathrm{MC}(t) - \mathrm{IC}(t)] \tag{8}$$

(details on variables are given in Table 3).

2.3.2. The environmental indicators Rpest, Rero, and Rfert

Some of the outputs or state variables of the biophysical modules provide input data to calculate indicators of potential environmental risks: Rpest for water exposure to pesticides (Tixier et al., 2007a), Rero for erosion, and Rfert for soil quality. Rero aggregates variables related to the field topography, the spatial organization of the crop on the field, the percentage of soil cover, the depth of ploughing, the soil compaction score, and the rain intensity. Rero was calibrated using data of Blanchart et al. (2002), Khamsouk (2001), Khamsouk et al. (2002) and Cattan et al. (2006). Rfert assesses the physical, chemical, and biological soil quality. Rfert aggregates variables related to the number of ploughings and mechanical passages, the imported/exported nitrogen ratio, the plant-parasitic nematode density, and the number of nematicide applications. Rfert was calibrated in particular using data of Feller (1995), Loranger et al. (1998) and Dorel (2001).

These indicators are based on the aggregation of variables, using an expert system and fuzzy logic (Girardin et al., 1999). By linking the model outputs and indicators, the simulated system is assessed on a weekly basis, whereas

Table 4
Variables used for the multicriteria assessment and relative weights in the multicriteria evaluation for the profit evaluation and for the environmental evaluation (mostly based on environmental criteria and keeping a 30% weight of profit to search for realistic systems that can be adopted by farmers)

Variables	Relative weight for the	
	Profit evaluation	Environmental evaluation
Total profit margin (euro ha^{-1})	1.00	0.30
Mean pesticide risk Rpest (score)	0.00	0.40
Mean erosion risk Rero (score)	0.00	0.10
Mean soil quality Rfert (score)	0.00	0.20

most existing indicators can be used only for annual assessments, and with data on farmers′ practices, as shown in the review of Van der Werf and Petit (2002). The erosion risk indicator Rero and the pesticide water pollution risk indicator Rpest are dynamic and hence can be used to detect periods of maximum environmental risk. The risk score generated every week can be integrated into the complete cropping period, with a mean score or a distribution of scores by classes. This output allows to compare different cropping systems. The Rpest indicator has been validated by experts (Tixier et al., 2007a).

2.3.3. Multicriteria evaluation

The four indicators described above have been used for the multicriteria evaluation of each banana-cropping system.

Their aggregation is based on a weighting method, considered the best for such a low number of variables. Two aggregated indicators have been defined: “profit” and “environmental”, depending on the weight given to each indicator (Table 4). The values of the individual indicators are re-scaled to a 0–10 range. In this way, they can be compared on the same scale, with 10 representing the best evaluation. These two aggregated indicators have been chosen as examples for the demonstration. However, the SIMBA model can be used with any other set of weights or with other multicriteria evaluation methods, chosen in consultation with stakeholders and policy makers.

3. Method to generate and assess cropping systems

To select the most promising cropping systems, a two-step approach has been used: an exhaustive exploration of decision rules (step 1) followed by a one-by-one optimization of the rules of the best combinations defined in step 1 (step 2). This two-step method makes it possible to conduct model-based design and can be used to pinpoint cropping systems that could be further on tested in the field (Fig. 4).

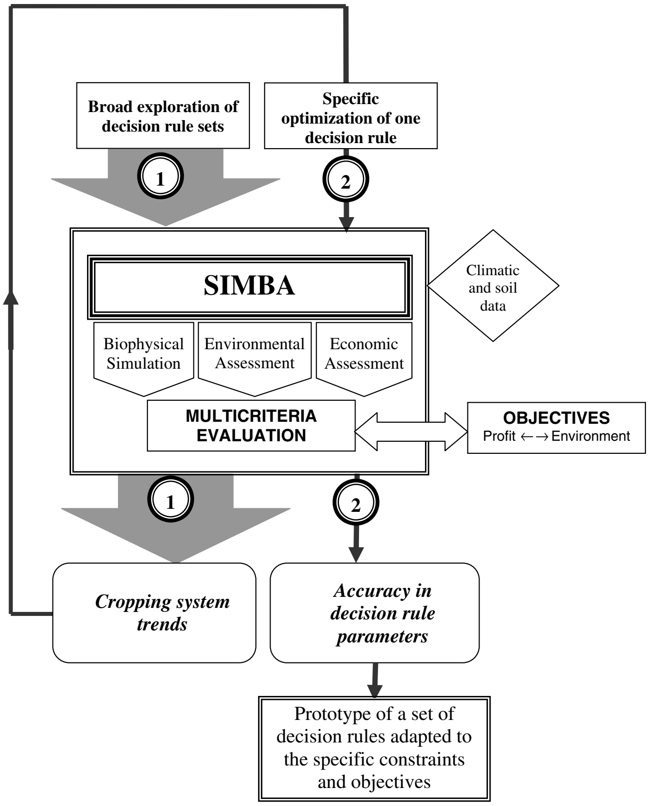

Fig. 4. Designing decision rules based on banana-cropping systems, using SIMBA in a two-step process: step 1 – exhaustive exploration of decision rule combinations, step 2 – one-by-one optimization of decision rules.

3.1. Exhaustive exploration of decision rule combinations (step 1)

SIMBA is used to explore a wide range of decision rule combinations in order to analyze the trends in cropping system impacts on profit and environment, for a given soil-climate condition. This exploration is performed by a specific module that automatically tests all the possible decision rule combinations. For each decision rule ‘*i*’, the associated control variable Vi is tested within its variation range (Vi_{min} to Vi_{max}, defined according to its characteristics) and with a step Si. The number of combinations (N) for n decision rules is given in Eq. (9).

$$N = \sum^{(i=1 \text{ to } i=n)} [(\mathrm{Vi}_{max} - \mathrm{Vi}_{min} + 1)/\mathrm{Si}] \tag{9}$$

After simulation of a high number of decision rules, the ranking and analysis are done in three steps:

- ranking the systems according to the selected aggregate indicator (profit or environmental),
- eliminating unfeasible systems, for agronomical reasons that the model cannot take into account (unusual),
- analyzing the systems with the best scores in order to highlight trends (if there is one or more).

SIMBA can be used to test and evaluate scenarios, e.g. monocultures or rotations with fallow or sugarcane. As

Table 5
Measured and evaluated initial soil, parasitic, environmental, and economic parameters of SIMBA for typical conditions of the previous crop after a 0.8 year fallow (from Tixier, 2004)

Parameters	Value after a 0.8 year fallow	Unit
Soil cover (%)	100	%
Soil compaction	2.5	score/10
Radopholus similis inoculum	0.05	Nbr. g^{-1}
Previous crop's environmental evaluation	9	score/10
Previous crop's profit margin	−400	euros

an example we present a broad exploration performed in the case of fallow-banana rotation systems, under fixed soil and climate conditions (andisol, 250 m elevation, climate of a mean year in Guadeloupe and planting in May) with a fallow period of 10 months for a maximum period of 500 weeks (following the replanting decision rules). The evaluation was performed over the banana-cropping period by using the initial simulation parameters presented in Table 5. The result is 4050 combinations of tactical and strategic decision rules (Table 1).

3.2. One-by-one optimization of decision rules (step 2)

When the trends have been determined, some of the decision rules (strategic or tactical) can be optimized one at a time with higher precision. Specific tests are particularly interesting for testing different control variables (Table 1) in order to find the most suitable ones. This second step is used to precisely determine decision rules that should be tested on-farm or used in a strategy. It includes testing all possible plantation weeks of the year, using a climate of a mean year. This allows to take into account the variability due to intra-annual variation of climate.

4. Results and discussion

4.1. Design and assessment of fallow-banana rotation systems

The best profit, the best environmental, and trade-offs for 4050 simulations are, respectively, in the right part, the upper part, and the upper right corner of Fig. 5. The agronomic practices associated with the first 10 systems of the profit evaluation and the environmental evaluation are characterized:

- for the profit target by systems that can be considered intensive, by 3–4 cropping cycles, a high level of nematicide application at planting, a medium to high level of fertilization, and a low fallen plant replacement threshold;
- for the environmental target, by 2–3 cropping cycles, a low nematicide application frequency, no plowing, and a low fertilization level associated with a low replacement level or a high fertilization level associated with a high replacement level (Table 6).

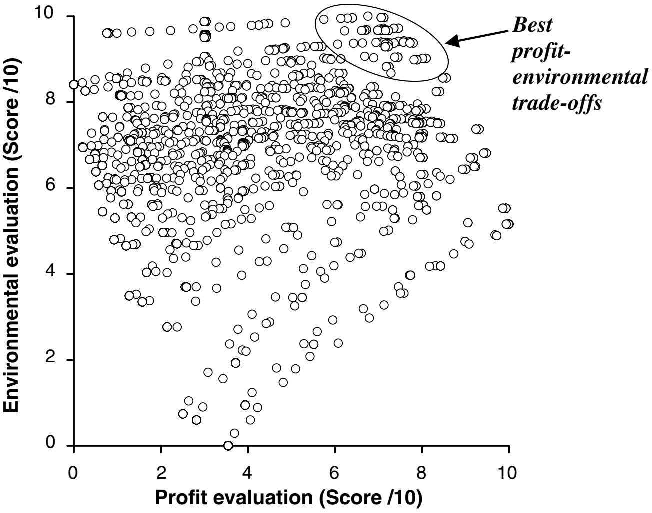

Fig. 5. Profit and environmental evaluation of 4050 simulations of fallow-banana rotation cropping systems.

The main difference between existing cropping systems and model recommendations is the number of cropping cycles before replanting. The model recommends fewer cropping cycles than farmers do (3–4 instead of 5–8). This strategy is perhaps over-rated because some phenomena have not yet been correctly weighted in the evaluation, such as the soil organic matter content, which is affected by frequent replanting and could lead to loss of soil fertility on the long term. A soil organic matter module is being developed to enhance the evaluation potential of SIMBA. Both the tactical and strategic optimizations could be potentially effective for reducing pesticide use and to enhance nematode control.

4.2. Optimization of specific tactical decision rules: when to replant banana?

To illustrate the second step of our methodology to design prototypes, we used SIMBA to optimize one specific decision rule for fallow-banana rotation cropping systems. Two control variables of the decision rules that drive replanting were tested. This strategic decision rule is at the core of the banana-cropping systems. Specific optimization involves testing all possible values for the control variables.

The control variables used to activate banana replanting were (i) the number of cropping cycles, (ii) and the yield of the last cropping cycle. The optimal number of cycles before replanting is of four for profit evaluation and four and more for environmental evaluation (Fig. 6A). This decision rule test highlights the fact that relatively frequent replanting is good for profit while more than four cycles gives a better environmental evaluation. This behavior may be explained by the fact that the harvest peak of each

Table 6
Description of the 10 best fallow-banana rotation cropping systems for the profit evaluation and for the environmental evaluation

Rank	Number of banana cycles	Weeks between nematicide	Soil mechanization	Fertilization		Falling plant management
				Dose (g plant^{-1})	Period (weeks)	
Profit evaluation						
1	4	20	Ploughing	130	3	Replacement at 15%
2	4	20	Ploughing	100	5	Replacement at 15%
3	4	20	Ploughing	130	3	Replacement at 15%
4	4	20	Ploughing	80	8	Replacement at 15%
5	3	20	Ploughing	100	5	Replacement at 30%
6	3	20	Ploughing	130	3	Replacement at 15%
7	3	20	Ploughing	100	5	Replacement at 30%
8	3	20	Ploughing	130	3	Replacement at 30%
9	3	20	Ploughing	100	5	Replacement at 15
10	3	20	Ploughing	130	3	Replacement at 15
Environmental evaluation						
1	3	80	No ploughing	130	3	Replacement at 15%
2	3	80	No ploughing	100	5	Replacement at 15%
3	3	80	No ploughing	130	3	Replacement at 15%
4	3	80	No ploughing	80	8	No replacement
5	3	80	No ploughing	80	8	Replacement at 15%
6	3	100	No ploughing	80	8	No replacement
7	2	60	No ploughing	100	5	Replacement at 30%
8	2	60	No ploughing	130	3	Replacement at 15%
9	2	60	No ploughing	100	5	Replacement at 30%
10	2	60	No ploughing	130	3	Replacement at 30%

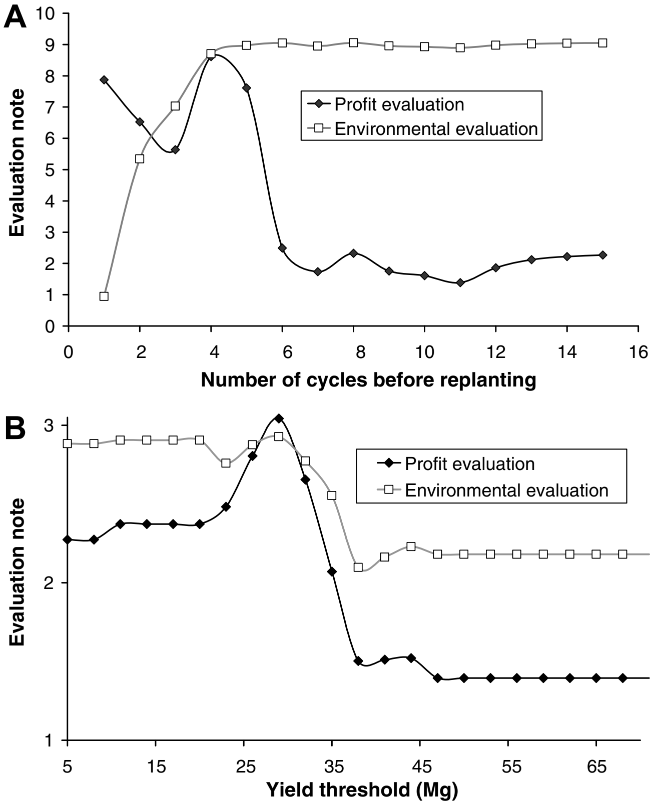

Fig. 6. Evaluation of a monoculture for all tested values of the two possible control variables that control replanting of the banana field: number of cropping cycles since planting (A) and yield of the last cropping cycle (B).

cropping cycle occurs at a precise time of the year. When harvest peaks become more spread after some cropping cycles, the farmer cannot target the high price period. The result is that frequent replanting can be economically advantageous to keep narrow harvesting peaks that occur during the high selling price periods (i.e. winter in Europe), in order to maximize the gross margin (Tixier et al., 2007b). The optimal yield thresholds under which it is better to replant is 29 Mg ha^{-1} for the profit evaluation and 20 (and lower) Mg ha^{-1} for the environmental evaluation (Fig. 6B). These results show that 29 Mg ha^{-1} is a value below which replanting leads to higher profit. A lower replanting frequency (associated with a lower threshold) is a better strategy for an environmental objective. We note that the control variable "number of cycles before replanting" has more effect than "yield threshold before replanting" on both profit and environmental evaluations. This is because the number of cycle has a strong and direct influence on the system's performances while yield is influenced by many other factors. As a result, the number of cycle is a more relevant and useful control variable.

5. Conclusion

The SIMBA model can be used to simulate and to assess different tactical and strategic decision rules of a banana crop with economic and environmental indicators calculated at each time-step of the model. It allowed simulation, evaluation, and hence comparison of thousands of different banana-based cropping systems in a given soil-climate situation. Complex sets of decision rules can be tested in an evaluation procedure or in system's design process. The results of the comparative analysis of the systems showed some interesting areas for improvement in the current cropping systems. SIMBA is an efficient tool for development programs aimed at reducing pesticide use, while keeping sufficient level of profit, which is the major challenge in the F.W.I.

Other model-based methods are founded only on biophysical models (Loyce et al., 2002a,b) and do not take into account the potential impact of pesticides use Here, we have taken advantage of biophysical models and qualitative models based on fuzzy logic for complex and integrated concepts (pesticide risk, soil quality). This enabled us to assess the systems on the basis of more criteria, thus providing a more realistic view of the simulated system with regards to sustainability. More criteria of evaluation could be taken into account; for instance, the risk to find residues in fruit as suggested by Tixier et al. (2007c) may constitute a particularly relevant sanitary criterion.

The two-step design method we proposed (wide screening of potential cropping systems and accurate optimization of the most promising ones) could be applied to many other systems and cropping system models. It serves to highlight a group of systems that could be tested in the field. The most promising systems to test should be selected in collaboration with stakeholders and farmers. Furthermore, as suggested by deVoil et al. (2006), more powerful algorithms could be used to explore decision rules combinations more efficiently.

This method does not seek to provide high precision values for each characteristic of the system. It also does not allow, in itself, to assess the system at higher levels than field scales (e.g. farm, watershed) which would be required for economic and environmental impact assessment. Instead, the goal is to sort the systems on the basis of a wide range of objectives. It is not meant to replace field experiments but rather to help choose the most relevant experiments for future research. Additionally, SIMBA can also be used to do 'strategic thinking' with farmers and stakeholders (Dogliotti et al., 2005).

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