Europ. J. Agronomy 41 (2012) 81–91

Contents lists available at SciVerse ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Modeling spatial partitioning of light and nitrogen resources in banana cover-cropping systems

Aude Ripoche*, Raphaël Achard, Aude Laurens, Philippe Tixier

CIRAD, UPR 26, Quartier Petit Morne, BP 214, F-97285 Le Lamentin, Martinique, France

ARTICLE INFO

Article history:
Received 26 September 2011
Received in revised form 14 March 2012
Accepted 3 April 2012

Keywords:
Intercropping
Resources partitioning
Nitrogen
Banana cover cropping system
Modeling

ABSTRACT

In banana cropping systems, cover crops are introduced mainly to manage weeds and mitigate the use of herbicides. But this introduction modifies the structure of the field, its biophysical functioning and then farmers' practices. We designed the SIMBA-IC model to simulate nitrogen and light partitioning and crop management, which can differ across the different zones of the field (banana row, small and large inter-rows), and to assess agronomic and environmental performances of banana cover cropping systems under scenarios of different spatial arrangement. We calibrated and validated the model using independent data sets from a fertilizer and an intercropping experiment, respectively. Results showed that SIMBA-IC realistically simulated the differences between treatments in terms of crop cycle duration (for flowering date, RMSE = 2.3 weeks in the calibration and validation steps) and biomass produced (RMSE = 0.67 and 0.94 kgDM ha^{-1} at flowering in calibration and validation steps, respectively). We simulated different management options related to the four field zones to optimize fertilization and cover crop management and ensure a tradeoff between agronomic (banana yield) and environmental (N leaching mitigation) performances. Simulations showed that yield was maximal and N leaching was reduced when fertilization was applied in the banana row. When cover crops were mowed according to the banana N stress, agronomic and environmental performances were higher than when mowing was based on the cover crop leaf area index, but the former approach led to very frequent mowing. Future studies should consider the impacts of these cropping systems from a socio-economic point of view to assess their feasibility and ability to be adopted.

1. Introduction

There is currently a surge in reintroducing biodiversity in agricultural systems to reduce chemical inputs, suppress pests, and close biogeochemical cycles (Altieri, 1999; Tilman et al., 2002). Cover crops are a concrete way to reintroduce biodiversity in fields (Teasdale, 1996) and are a frequent option for weed management (Moonen and Barberi, 2008). Cover crops generate different services (e.g. mitigate soil erosion, Derpsch et al., 1986; increase soil carbon and nitrogen and improve microbial activity, Ramos et al., 2010) and they have the potential to decrease chemical control of weeds and pests. Nevertheless, adding cover crops alters the functioning of the system, especially flows of water and nutrients (Celette et al., 2008; Mazzoncini et al., 2011; Singer et al., 2011). If cover crops are introduced, farmers have to adapt their practices of fertilization, irrigation, and weed management. As different zones can be defined within a banana field according to the plant they hold (banana, cover crop, or none), spatial differentiation of cultural practices is an interesting option to manage 'cultivated crop-soil-cover crop' interactions. Management of fertilization, irrigation, or cover crop mowing related to the different zones of the field can help minimize the competition between cover crop and cultivated crop (Ripoche et al., 2011) and the environmental impacts (especially nutrient losses). Spatialization of cultural practices is particularly suitable for row-cultivated plants, e.g. orchards, vineyards, palm trees, and bananas.

Export bananas cover nearly one million ha worldwide. Banana cropping systems remain based on bare soil and thus use large quantities of herbicides, 3–4 kg ha^{-1} $year^{-1}$ of herbicide active products in the French West Indies (Chabrier, Pers. Com.). Environment quality is adversely affected by the frequent applications of these herbicides 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 and Martinique, where inhabited areas, coral reefs, and rainforests are close to agro-systems (Bonan and Prime, 2001; Bocquene and Franco, 2005). In this context, farmers and extensionists require that the sustainable cropping systems designed allow maintaining a satisfactory level of banana yield and mitigate the use of pesticides.

* Corresponding author. Present address: CIRAD UPR SCA, Avenue Agropolis, TA B 102/02 (Bât. 7, Bur. 13) – 34398 Montpellier Cedex 5, France.
Tel.: +33 4 67 61 71 28; fax: +33 4 67 61 56 66.
E-mail address: aude.ripoche@cirad.fr (A. Ripoche).

1161-0301/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.eja.2012.04.001

Models are increasingly used to assist the design of innovative cropping systems (Wery and Langeveld, 2010). Models are useful tools to explore innovative assemblages of cultural practices and to optimize particular ones (Dorel et al., 2008; Tixier et al., 2008, 2011). Most crop models consider nitrogen in a field through a single compartment (Parton and Rasmussen, 1994) or through horizontal layers (Brisson et al., 2003). More complex models include a vertical two-dimension or a three-dimension representation of water and nitrogen flows over the fields (Doltra and Munoz, 2010). There are very few models linking the functioning of different zones with farmers' practices differentiated between zones and that remain tractable to calibration and validation. Horizontal zones are relevant units of simulation because they correspond to the level at which farmers manage their fields.

In this paper, we describe and validate a zone model called SIMBA-IC that simulates banana and cover crop growth, and their interaction in exploitation of nitrogen (N) resources according to four contrasted horizontal zones. We assume that modeling the four zones within the field allows representing and testing different spatial field managements, and assessing their agronomic and environmental performances. This model aims at helping design of cover cropping systems in terms of both environmental (reducing N leaching) and productive (yield) criteria. Here, we explored how the spatial organization of practices (fertilization, cover crop and crop residue management) can optimize the performances of cropping systems. The model was built by assembling existing and new modules, both specifically designed for banana cropping systems, with an emphasis on biologically meaningful parameters. The model was calibrated and validated using two distinct datasets, a fertilization experiment and an intercropping experiment. We propose an application of the model to evaluate the banana yield and nitrogen losses for scenarios of cover crop management and fertilization differentiated between zones.

2. Materials and methods

2.1. Field data

Two independent data sets from Martinique (experimental station of Rivière Lézarde, French West Indies) were used to calibrate and validate the SIMBA-IC model: a fertilizer experiment and an intercropping experiment. The fertilizer experiment was carried out in a field called Pavé (14°39′32″N–60°59′33″W) during 2005 and 2006. The intercropping experiment was carried out in a field called Ponterre (14°39′44″N–60°59′57″W) during 2006–2008. The details of sampling are presented in Table 1. Temperature, rainfall, evapo-transpiration (ETP), and solar radiation (Rg) were recorded on the fields by a Campbell Scientific™ meteorological station (Sheperd, UK) beside the plot at one meter above the ground.

2.1.1. Fertilizer experiment

In this two-year experiment, four nitrogen fertilization treatments were tested with four replicates; ten banana crops were observed in each unit plot. Four contrasted levels of nitrogen fertilizer were tested: 30 (F0), 170 (F1), 300 (F2), and 440 kgN ha^{-1} (F4). At planting, in vitro plantlets received as starter fertilization 6 kgN ha^{-1} and 30 kgP ha^{-1}. After two weeks, all treatments received N fertilizer and the same amount of P and K fertilizer (150 kgP ha^{-1} year^{-1} and 600 kgK ha^{-1} year^{-1}) split in monthly applications to ensure a non limited nutrition in P and K. Amounts and week of application of N in the different treatments are detailed in Table 2. Banana crop residues were spread all over the surface of the field. Basal girth of banana pseudo-stems, leaf length, and leaf width were measured monthly until flowering. Bunches were harvested and weighed. A relationship between basal girth and fresh biomass was previously established (Achard, Pers. Com.), and the fresh biomass was estimated according the following equation:

$$\mathrm{FBiom} = a \times \mathrm{BasalGirth} + b$$

where $a = 2.07$ and $b = -73.79$ before flowering, and $a = 3.28$ and $b = -109.52$ at flowering.

2.1.2. Intercropping experiment

In this three-year experiment, three treatments were tested with five replicates. Twenty banana crops were observed in each unit plot. A common P and K fertilizer program ensured non limited nutrition in P and K: 150 kgP ha^{-1} year^{-1} and 600 kgK ha^{-1} year^{-1} split in monthly applications. The tested treatments included two intercropping treatments with cover crops (*Brachiaria decumbens*, BD, and *Cynodon dactylon*, CD), and a bare soil treatment (BS). The cover crops were sown all over the field 1 December 2005. Schedules of fertilizer applications and mowing, and amounts of N applied are presented in Table 2. Cover crop residues were left in their area of growing after mowing whereas banana residues were moved into the small inter-row at harvest. Basal girth of banana pseudo-stems, leaf length, and leaf width were measured monthly until flowering. Fresh biomass was estimated from the same equation as for the fertilizer experiment. Bunches were harvested and measured. Fresh cover crop biomass was measured by cutting the cover at soil level into two parcels per plot of 0.5 m × 0.5 m, before and after mowing during two cropping cycles (week 1, 9, 30, 34 and 54). Dry biomass was estimated on the basis of dry matter content of a 100 g fresh aliquot of the two samples cut in each unit plot.

2.2. Model description

2.2.1. Model structure

SIMBA-IC was developed using STELLA® (software environment from High Performance System®, Lebanon, NH). SIMBA-IC was designed to take into account the different zones that can be defined within a field (Fig. 1) and therefore their different N dynamics according to the management operated on each zone: fertilizer application, cover crop management, banana growth. This model simulates banana and cover crop growth and N dynamics in soil at weekly steps; its general structure is represented in Fig. 2. The different modules used to build SIMBA-IC were built at weekly steps. This corresponds to the precision that farmers use to manage their fields and is sufficient for cropping systems design. The light available for the cover crop was calculated taking the shading effect of banana into account for each of the four zones. In each of the four zones defined in SIMBA-IC, it is possible to carry out distinct operations (fertilization, cover cropping, mowing, restitution of banana and cover crop residues). For N resources, the partitioning allows representing the banana N uptake variations in relation to soil exploration by banana roots. The cover crop is assumed to explore

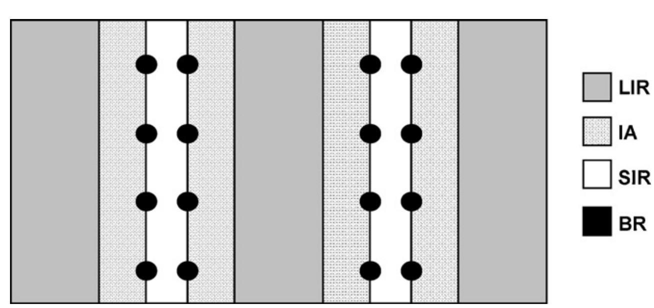

Fig. 1. Description of the different zones in a banana field, with BR, SIR, IA, and LIR corresponding to banana row, small inter-row, intermediate area, and large inter-row, respectively.

Table 1
Data sets used for calibration and validation of SIMBA-IC.

Field	Treatment	Number of crop cycles observed	Number of data samplings	Uses
Pavé	F0 (30 kgN ha^{-1})	2	12	Calibration
	F1 (170 kgN ha^{-1})	2	13	Calibration
	F2 (300 kgN ha^{-1})	2	13	Calibration
	F3 (440 kgN ha^{-1})	2	11	Calibration
Ponterre	Bare soil (BS)	3	11	Validation
	Cover cropped with *Brachiaria decumbens* (BD)	3	11	Validation
	Cover cropped with *Cynodon dactylon* (CD)	3	11	Validation

Table 2
Fertilization schedules for fertilizer and intercropping experiments. In the intercropping experiment, the three treatments received the same quantity of fertilizer.

	Week of mowing	Week of fertilizer application	Amount of N mineral (kgN ha^{-1})
Pavé (fertilizer experiment)	–	0	3
		After week = 2, every 4 weeks	F0 = 1.2 F2 = 8.1 F2 = 15 F3 = 21.9
Ponterre (intercropping experiment)	1–9–18–30–34–44–54–67–76–95–115	0	17
		4–7	27
		From week 10 to 34, every 4 weeks	34
		From week 41 to 95, every 4 weeks	27

Table 3
Description of the parameters used in the SIMBA-IC model.

Parameters	Unit	Description	Value	Source
aban; bban	–	Parameters of banana biomass production as a function of $PARi_{n,t}$	−0.2211; 25.525	Adapted from Nyombi et al. (2009)
acc; bcc	–	Parameters of cover crop biomass production as a function of $PARicc_{n,t}$	$acc_{Bd} = -5E-5$; $bcc_{Bd} = 0.01$ $acc_{Cd} = -9.29E-5$; $bcc_{Cd} = 8.18E-3$	Tixier et al. (2011)
k	–	Extinction coefficient of banana crop	0.7	Nyombi et al. (2009)
kcc	–	Extinction coefficient of cover crop	$kcc_{Bd} = kcc_{Cd} = 0.5$	Tixier et al. (2011)
ksen	LAI w^{-1}	Senescence rate before/after flowering	0.013; 0.025	Observed in Pavé experiment
ksu_{min}	–	Minimal allocation rate at floral initiation to sucker for the first/following cropping cycles	0/0.1	Calibrated in Pavé experiment
ksu_{max}	–	Maximal allocation rate at flowering to sucker for the first/following cropping cycles	0.25/0.35	Calibrated in Pavé experiment
$LAImax_i$	$m^2\ m^{-2}$	Leaf area index for maximal photosynthetically active radiation intercepted by banana in zone ‘i’	$LAImax_{sir} = 2$; $LAImax_{ia} = 3$; $LAImax_{lir} = 5$	Tixier (pers. comm.)
nstress	kg ha^{-1}	Minimal amount of mineral nitrogen available for banana crop	38	Calibrated in Pavé experiment
p	–	Proportion of PAR intercepted	0.456	Monteith (1972), Tixier et al. (2011)
$Pintmax_i$	–	Proportion of maximal PAR intercepted by banana in zone ‘i’	$Pintmax_{sir} = 0.7$; $Pintmax_{ia} = 0.7$; $Pintmax_{lir} = 0.6$	Tixier (pers. comm.)
pz_i	%	Percentage of the field attributed to the zone ‘i’	$pz_{br} = 20$; $pz_{sir} = 20$; $pz_{ia} = 20$; $pz_{lir} = 40$	Observed in Pavé experiment
			$pz_{br} = 23$; $pz_{sir} = 10$; $pz_{ia} = 19$; $pz_{lir} = 48$	Observed in Ponterre experiment
pl	%	Percentage of leaves	34	Pavé
pn	%	Percentage of nitrogen in tissues	$pn_{Bd} = 1.65$; $pn_{Cd} = 1.06$	Tixier et al., 2011
SF_IF	m^2	Foliar surface for floral initiation (1st crop cycle/following ones)	12/15	Adapted from Jannoyer (1995)
sla	$m^2\ kg^{-1}$	Massic surface	7.4	Observed in Pavé experiment
sub	m^2 $plant^{-1}$	Surface of a banana crop	Pavé: 5.05 Ponterre: 5.435	
SUMT IFF	°C	Sum of degree-days between floral initiation and flowering (1st crop cycle/following ones)	600/800	Observed in Pavé experiment
SUMT FH	°C	Sum of degree-days between flowering and harvest (1st crop cycle/following ones)	950/1000	Observed in Pavé experiment

With *i*, the zone considered in the model; BR = banana row, SIR = small inter-row, IA = intermediate area, LIR = large inter-row. Bd = Brachiaria decumbens, Cd = Cynodon dactylon.

Table 4
Description of the variables simulated by the SIMBA-IC model.

Variables	Unit	Description
$Inhib_{n,t}$	–	Inhibition coefficient of the sucker by the "main" banana during crop cycle '*n*' at step '*t*'
$Kstress_t$	–	Banana N stress at step '*t*'
$Kstresscc_{i,t}$	–	Cover crop N stress in zone '*i*' at step '*t*'
$Ksu_{n,t}$	–	Allocation coefficient for bunch biomass
$Kveg_{n,t}$	–	Allocation coefficient for vegetative biomass
$Pint_{i,t}$	%	Percentage of PAR intercepted by banana crop in zone '*i*' at step '*t*'
$Rl_{i,t}$	%	Percentage of soil explored by banana root length
$\Delta biom_{n,t}$	kgDM plant^{-1}	Biomass newly formed during crop cycle '*n*' at step '*t*'
$\Delta biomveg_{n,t}$	kgDM plant^{-1}	Vegetative biomass newly formed during crop cycle '*n*' at step '*t*'
$\Delta biombun_{n,t}$	kgDM plant^{-1}	Bunch biomass newly formed during crop cycle '*n*' at step '*t*'
$\Delta biomsu_{n,t}$	kgDM plant^{-1}	Sucker biomass newly formed during crop cycle '*n*' at step '*t*'
$Biomveg_{n,t}$	kgDM plant^{-1}	Vegetative biomass during crop cycle '*n*' at step '*t*'
$Biombun_{n,t}$	kgDM plant^{-1}	Bunch biomass during crop cycle '*n*' at step '*t*'
$F_{i,t}$	kgN ha^{-1}	Mineral N fertilized at step '*t*'
$\Delta LAI_{n,t}$	m^2 m^{-2}	LAI newly formed during crop cycle '*n*' at step '*t*'
LAI_t	m^2 m^{-2}	Total banana leaf area index at step '*t*'
$LAI_{n,t}$	m^2 m^{-2}	Banana leaf area index during crop cycle '*n*' at step '*t*'
$LAIcc_{i,t}$	m^2 m^{-2}	Cover crop leaf area index in zone '*i*' at step '*t*'
$L_{i,t}$	kgN ha^{-1}	Mineral N leached in zone '*i*' at step '*t*'
Ncci,t	kgN ha^{-1}	Mineral N cover crop demand in zone '*i*' at step '*t*'
$Nmin_{i,t}$	kgN ha^{-1}	Soil mineral N in zone '*i*' at step '*t*'
$Nminban_{i,t}$	kgN ha^{-1}	Soil mineral N available for banana crop in zone '*i*' at step '*t*'
$Ntotban_t$	kgN ha^{-1}	Soil mineral N available for banana crop at step '*t*'
$PARi_t$	J m^{-2}	Photosynthetically active radiation intercepted at step '*t*'
$PARi_{n,t}$	J m^{-2}	Photosynthetically active radiation intercepted by banana during crop cycle '*n*' at step '*t*'
$PARicc_{i,t}$	J m^{-2}	Photosynthetically active radiation intercepted by cover crop at step '*t*'
$Rban_{i,t}$	kgN ha^{-1}	Mineralized N from banana residues in zone '*i*' at step '*t*'
$Rcc_{i,t}$	kgN ha^{-1}	Mineralized N from cover crop residues in zone '*i*' at step '*t*'
Rg_t	J m^{-2}	Total radiation at step '*t*'
$S_{i,t}$	kgN ha^{-1}	Mineralized N from soil organic matter in zone '*i*' at step '*t*'
$Uban_{i,t}$	kgN ha^{-1}	Mineral N uptake by banana in zone '*i*' at step '*t*'
$Ucc_{i,t}$	kgN ha^{-1}	Mineral N uptake by cover crop in zone '*i*' at step '*t*'

With *t* the time step of the model in weeks, *n* the cropping cycle, and *i* the zone considered in the model.

exclusively soil in the zone in which it is growing, as was observed and simulated for vineyard cropping systems (Celette et al., 2008, 2010). All parameters and variables are described in Tables 3 and 4.

2.2.2. Banana growth module

The algorithms to simulate banana growth were adapted from Tixier et al. (2008). The main equations are presented in Table 5. The banana phenology is driven by growth variables and temperature. Floral initiation is simulated when the total foliar surface produced since planting exceeds a threshold (Jannoyer, 1995); then, floral initiation-flowering interval and flowering-harvest interval are driven by degree-days (base temperature = 14 °C, Ganry, 1980). The biomass produced is calculated according to the radiation intercepted by banana (Eq. (1)) and its conversion into biomass, according to a parabolic relationship (Eq. (2)). From floral initiation until flowering, we assumed that the biomass newly produced was allocated to vegetative and reproductive biomass ($Biomveg_{n,t}$ and $Biombun_{n,t}$, respectively). A part of reproductive biomass was also allocated to the sucker ($Biomsu_{n,t}$; see Eqs. (3) to (8)) according to the coefficient $Kveg_{n,t}$, which varies from 1 to 0 between floral initiation and flowering. At flowering, we assumed that the biomass produced was exclusively allocated to reproductive biomass and

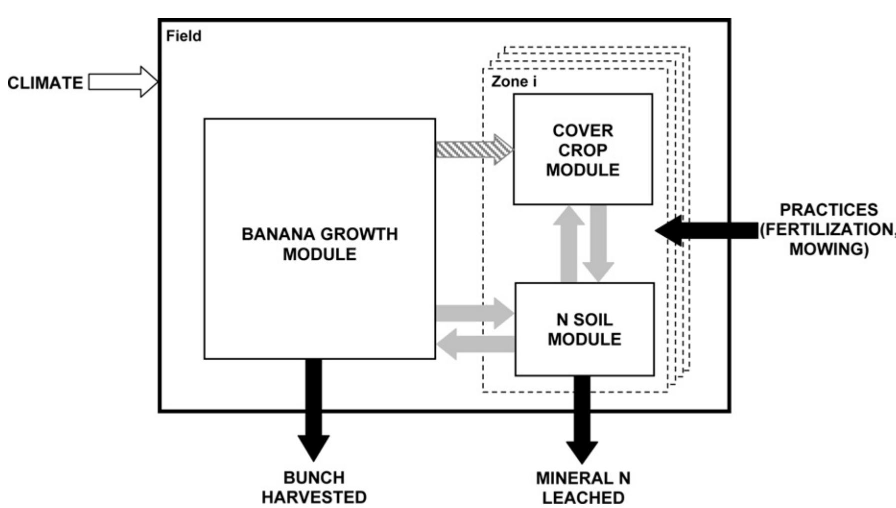

Fig. 2. General structure of the SIMBA-IC model. The white arrow represents climate inputs (radiation, temperature, rainfall and evapo-transpiration); black arrows represent inputs related to practices (e.g., fertilization or mowing activation) and outputs of nitrogen or biomass; gray arrows represent nitrogen flows within the system; the hatched arrow represents the shading effect of banana on cover crop.

Table 5
List of SIMBA-growth and SIMBA-N modules; all parameters and variables are described in Tables 2 and 3.

Equation	
Growth module (adapted from Tixier et al., 2008)	
$\text{PARi}_{n,t} = p \cdot \text{Rg}_t \cdot (1 - \exp^{(-k \cdot \text{LAI}_{n,t})}) - \text{PARi}_{n-1,t}$	(1)
$\Delta\text{biom}_{n,t} = (\text{aban} \cdot \text{PARi}^2_{n,t} + \text{bban} \cdot \text{PARi}_{n,t}) \cdot \text{Inhib}_{n,t} \cdot \text{Kstress}_t + \Delta\text{biomsu}_{n-1,t}$	(2)
$\Delta\text{biomveg}_{n,t} = \text{Kveg} \cdot \Delta\text{biom}_{n,t}$	(3)
$\Delta\text{biombun}_{n,t} = (1 - \text{Kveg}_{n,t}) \cdot (1 - \text{Ksu}_{n,t}) \cdot \Delta\text{biom}_{n,t}$	(4)
$\Delta\text{biomsu}_{n,t} = (1 - \text{Kveg}_{n,t}) \cdot \text{Ksu}_{n,t} \cdot \Delta\text{biom}_{n,t}$	(5)
$\text{Biomveg}_{n,t} = \text{Biomveg}_{n,t-1} + \Delta\text{biomveg}_{n,t}$	(6)
$\text{Biombun}_{n,t} = \text{Biombun}_{n,t-1} + \Delta\text{biombun}_{n,t}$	(7)
$\text{Biomsu}_{n,t} = \text{Biomsu}_{n,t-1} + \Delta\text{biomsu}_{n,t}$	(8)
$\Delta\text{LAI}_{n,t} = (\Delta\text{biomveg}_{n,t} \cdot \text{pl} \cdot \text{sla})/\text{sub}$	(9)
$\text{LAI}_{n,t} = \text{LAI}_{n,t-1} + \Delta\text{LAI}_{n,t} - \text{LAI}_{n,t-1} \cdot \text{ksen}$	(10)
$\text{LAI}_t = \sum_{n=1}^{5} \text{LAI}_{n,t}$	(11)
Cover crop module (adapted from Tixier et al., 2011)	
$\text{Pint}_{i,t} = \text{Pintmax}_i/\text{LAImax}_i \cdot \text{LAI}_t$	(12)
$\text{PARicc}_{i,t} = (\text{p} \cdot \text{Rg}_t - \text{PARi}_t \cdot \text{Pint}_{i,t}) \cdot (1 - \exp^{(-\text{kcc} \cdot \text{LAIcc}_{i,t})})$	(13)
$\Delta\text{biomcc}_{i,t} = (\text{acc} \cdot \text{PARicc}^2_{i,t} + \text{bcc} \cdot \text{PARicc}_{i,t}) \cdot \text{Kstresscc}_{i,t}$	(14)
$\text{Biomcc}_{i,t} = \text{Biomcc}_{i,t-1} + \Delta\text{biomcc}_{i,t}$	(15)
$\text{Ncc}_{i,t} = \Delta\text{biomcc}_{i,t} \cdot \text{pz}_i \cdot \text{pn} \cdot 10000$	(16) [a]
$\text{Kstresscc}_{i,t} = \text{If}(\text{Ncc}_{i,t} = 0)\,\text{Then}\,(1)\,\text{Else}\,(\text{Ncc}_{i,t}/\text{Ucc}_{i,t})$	(17)
N module (adapted from Dorel et al., 2008)	
$\text{Nmin}_{i,t} = \text{F}_{i,t} + \text{S}_{i,t} + \text{Rcc}_{i,t} + \text{Rban}_{i,t} - \text{L}_{i,t} - \text{Uban}_{i,t} - \text{Ucc}_{i,t}$	(18)
$\text{Nminban}_{i,t} = \text{Nmin}_{i,t} \cdot \text{Rl}_{i,t}$	(19)
$\text{Ntotban}_t = \sum_{i=1}^{4} \text{Nminban}_{i,t}$	(20)
$\text{Kstress}_t = \text{If}(\text{Ntotban}_t < \text{nstress})\ \text{Then}\,(\text{Ntotban}_t/\text{nstress})\ \text{Else}\,(1)$	(21)

With t the time step of the model in weeks, n the cropping cycle, and i the zone considered in the model.
[a] The unit of this constant = m^2.

therefore allocated to bunch and sucker. The coefficient $\text{Ksu}_{n,t}$ represents the biomass allocation to sucker between floral initiation and flowering and varies from Ksu_{min} to Ksu_{max}. We assumed that priority was given to bunch during the first cropping cycle, and the values of Ksu_{min} to Ksu_{max} were therefore lower than for the following cropping cycles (Table 3). This module also includes the inhibition of sucker by mother banana, which varies according to banana N stress and phenological stage. The inhibition coefficient $\text{Inhib}_{n,t}$ varies from 0 to 0.5 between floral initiation and harvest according to the N stress applied on banana. We assumed that if the nstress parameter was severe (Tables 4 and 5) and lower than 0.5, the inhibition was total ($\text{Inhib}_{n,t} = 0$). At harvest, as the mother plant is cut, $\text{Inhib}_{n,t}$ no longer has an effect on sucker biomass ($\text{Inhib}_{n,t} = 1$; see Table 5, Eq. (2)). Leaf area index (LAI) is calculated with the biomass newly produced at every time step and is reduced by senescence (Eqs. (9) to (11)). Two senescence rates were considered (before and after flowering) according to measured data (unpublished data).

2.2.3. Cover crop growth module

Equations describing cover crop growth were adapted from Tixier et al. (2011). In each zone, radiation intercepted by cover crop was calculated as a proportion of the banana LAI (Eq. (12), Table 5). The maximal value of PAR intercepted by banana and banana LAI differed between zones (Table 3). The cover crop biomass was calculated according to a radiation interception equation and its conversion into biomass according to a parabolic relationship (Eqs. (13) to (15)). The N stress coefficient applied to cover crop was defined in relation to the cover crop N demand and the available mineral N in the considered zone (Eqs. (16) and (17)).

2.2.4. Nitrogen balance module

Nitrogen balance module was adapted from Dorel et al. (2008) and Raphael et al. (2012); it simulates for each zone the mineral N dynamics in soil based on inputs (fertilization, soil organic matter, banana and cover crop residues mineralization) and outputs (crop uptakes, leaching; Eq. (18), Table 5). The mineral N available for banana in each zone depends on the banana roots' exploration (Eq. (19)). The higher the distance from the banana row, the lower the ability for banana roots to uptake N (Fig. 3). The total N available for banana is the sum of the N available in all zones (Eq. (20)). Banana and cover crop residues are produced according to harvest and mowing dynamics and are thus mineralized according to their time after return to soil, with the same equation as in Dorel et al. (2008). As for cover crops, N stress coefficient applied to banana is calculated using the ratio between N demand and mineral N available for banana crop (Eq. (21), Table 5).

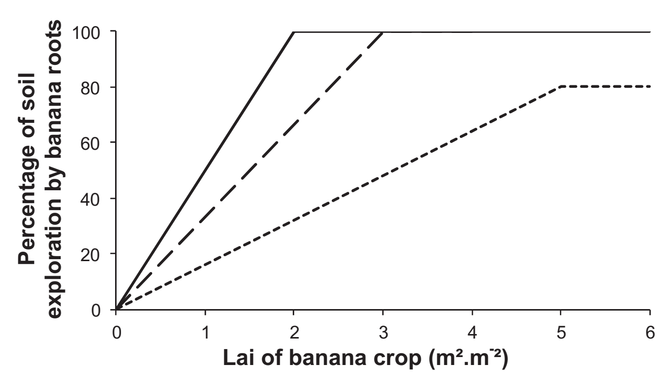

Fig. 3. Percentage of soil exploration by banana roots related to the LAI of banana crop related to the zone considered in the field: large inter- row (- - -), intermediate area (– – –), small inter-row (—). For the banana row, the percentage is maximal whatever the banana LAI.

2.3. Statistical analysis and modeling procedures

2.3.1. Model calibration

Most parameters were calibrated using literature values (Dorel et al., 2008; Tixier et al., 2008, 2011). nstress, ksu_{min}, and ksu_{max} were estimated using an iterative procedure in order to minimize the root mean square error (RMSE) of the banana vegetative biomass over the four treatments of the fertilizer experiment (Table 1 and Section 2.1.1).

2.3.2. Model evaluation

SIMBA-IC was evaluated with data from the intercropping experiment carried out over three crop cycles in 2006–2008 (Table 1 and Section 2.1.2). We compared the observed and predicted value of banana and cover crop vegetative biomass and calculated the RMSE. We also evaluated the model relative to the flowering date and banana vegetative biomass at flowering, which is an accurate yield indicator (Nyombi et al., 2009).

2.4. Cropping system design

Simulations were carried out over three banana crop cycles, using the climate inputs (solar radiation, evapotranspiration, air temperature and rainfall) of Rivière Lézarde (14°N, 60°W), which is representative of the growing condition of central Martinique, from 2008 to 2010.

2.4.1. Fertilization efficiency: effects of the amount and the zone of application

Simulations were carried out over three banana crop cycles to assess the efficiency of fertilization according to the zone of application and the amount of fertilizer. In this simulation study, the banana field was maintained on bare soil. The fertilizer amount varied between 0 and 450 kgN ha^{-1} with a 5 kgN ha^{-1} step. Fertilization occurred every month. Banana residues were left in the small inter-row at harvest. The evolution of banana yield, flowering date, and biomass at flowering as well as the N leached at field scale were analyzed for the three crop cycles simulated on the four zones considered in the model.

2.4.2. Efficiency of the layout of cover crop residues

In these simulations, the cover crop tested was *Brachiaria decumbens*, parameterized with parameter values from Tixier et al. (2011), sown at the beginning of the simulation (as banana plants) in the small and large inter-row as well as in the transition zone. Mowing was activated two ways: related to the cover crop LAI (mowing activated when LAI > 5) or related to the banana nitrogen stress (mowing activated when banana stress was lower than 0.5). After mowing, residues were left in the zone of cover crop growth, or concentrated in the small inter-row, the large inter-row, or the transition zone. Banana residues after harvest were applied in the small inter-row. Three contrasted levels of fertilization were tested: 150, 300, and 450 kgN ha^{-1} year^{-1}. Fertilization was applied every month. The evolution of banana yield, flowering date, and biomass at flowering for the three crop cycles simulated were analyzed on the four zones considered in the model, as the amount of N leached.

3. Results

3.1. Model calibration

The iterative procedure allowed determining the nstress parameter at 38 kgN ha^{-1}, ksu_{min} at 0 then 0.1, and ksu_{max} at 0.25 then 0.35 for the first and following cycles, respectively. The comparisons between observed and predicted dynamics of vegetative biomass of banana were satisfactory for both crop cycles studied (Fig. 4). The observed and predicted values of biomass at flowering showed satisfactory results, with a low value of RMSE (RMSE = 0.67 kgDM plant^{-1}, Fig. 5a). As for observed values, the simulated biomass of the first cropping cycle remained lower than that of the second cropping cycle for all treatments (7.0 ± 0.5 kgDM plant^{-1} vs. 9.6 ± 0.1 kgDM plant^{-1} on average, respectively). The comparison between observed and predicted date of flowering also showed that the dynamics of vegetative biomass were well simulated (RMSE = 2.3 weeks, Fig. 5b) except for F0, for which the flowering of the second cropping cycle was simulated with 5 weeks of delay.

3.2. Model evaluation

Fig. 6 presents comparisons between observed and predicted values of vegetative banana and cover crop biomass in the case of the intercropping experiment. Observed and predicted values of vegetative banana biomass at flowering and date of flowering were compared (Fig. 6a and b). The model slightly underestimated the biomass at flowering but predictions were satisfactory (bias = −0.62 and RMSE = 0.94 kgDM plant^{-1}; Fig. 6a). The difference between the first and the following crop cycles in terms of vegetative biomass produced was well simulated (6.5 ± 0.4 kgDM plant^{-1} vs. 9.6 ± 0.2 and 11.4 ± 0.03 kgDM plant^{-1} for the first, second, and third cropping cycles, respectively). Dates of flowering were accurately simulated (RMSE = 2.3 weeks; Fig. 6b). Nevertheless, the flowering of the second and third cropping cycles of CD treatments was simulated four weeks earlier. Comparison between observed and predicted values of cover crop biomass showed that the model was able to simulate the variations in cover crop biomass production due to mowing (Fig. 6c) despite a trend in underestimation (bias = −0.07 and −0.25 tDM ha^{-1} for CD and BD treatments, respectively). No treatment effect was observed between treatments.

3.3. Cropping system design

3.3.1. Fertilization efficiency

Simulation results showed that fertilization was more efficient in terms of agronomic performances when applied in the banana row (Figs. 7 and 8). For all zones, the higher the fertilization level, the earlier the flowering dates. The highest differences were observed when fertilization was applied under banana row, as flowering date occurred 43, 61, and 78 weeks earlier when fertilization was 450 kgN ha^{-1} year^{-1} than when fertilization was null. For the first banana crop cycle and the highest fertilization amount, flowering date occurred on average 11, 17, and 24 weeks earlier when fertilization was applied under banana row than when fertilization was applied in small inter-row, transition zone, and large inter-row, respectively (Fig. 7). When fertilization was applied under banana row, flowering date remained relatively stable above 300 kgN ha^{-1} year^{-1} of fertilization for the three crop cycles.

Fertilization under banana row was also more efficient in terms of yield and N leached. Lower performances were observed when fertilization occurred in the large inter-row (Fig. 8). For fertilization between 70 and 300 kgN ha^{-1} year^{-1}, the annual average N leached was always lower when fertilization was applied under banana row than in the other zones of the field. The higher the level of fertilizer applied, the higher the differences between treatments in terms of N leaching (up to 146 ± 3 kgN ha^{-1} year^{-1} vs. 221 ± 29 kgN ha^{-1} year^{-1} of N leached with fertilization of 70 and 300 kgN ha^{-1} year^{-1}, respectively). With fertilization of 70–300 kgN ha^{-1} year^{-1}, yields varied from 10 to 20, 19, 18, and 17 tDM ha^{-1} year^{-1} when fertilizer was applied under banana row, transition zone, small or large inter-row, respectively.

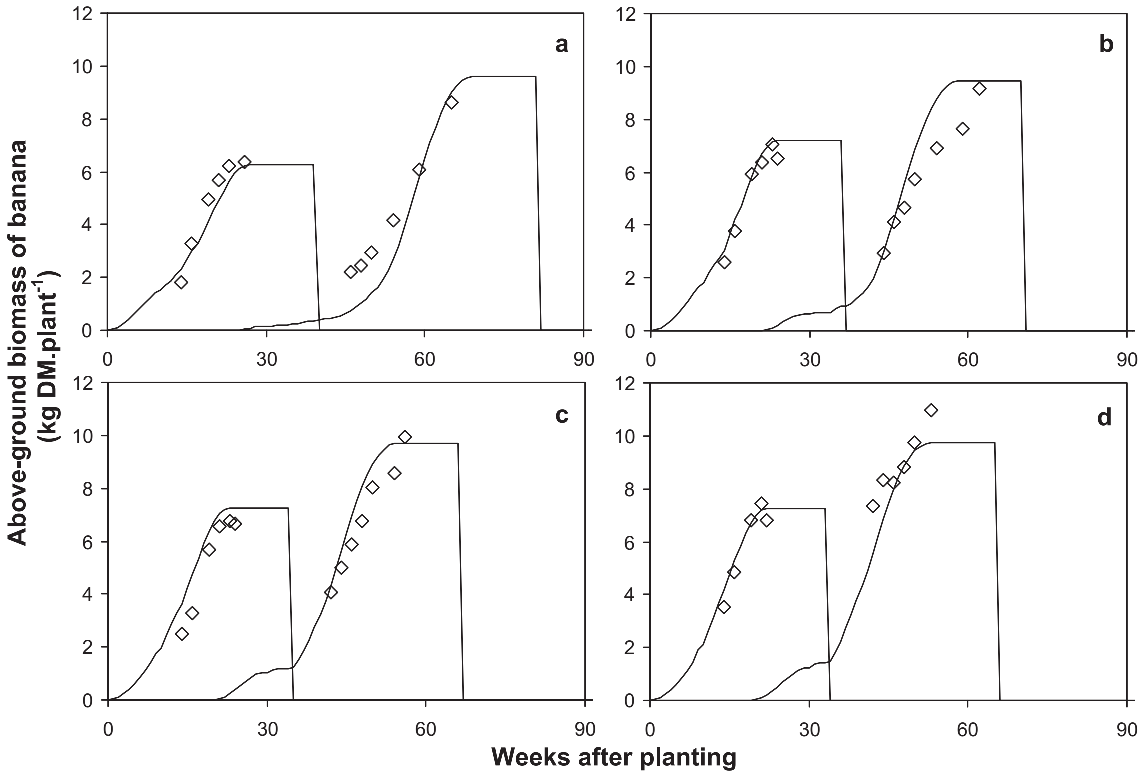

Fig. 4. Simulated and observed (◊) dry matter (DM) of above-ground biomass in banana cropping systems over two successive crop cycles under four levels of fertilization (a) 30 kgN ha^{-1}, (b) 170 kgN ha^{-1}, (c) 300 kgN ha^{-1}, (d) 440 kgN ha^{-1}.

3.3.2. Efficiency of layout of the cover crop residues

For fertilization of 150 and 300 kgN ha^{-1} year^{-1}, yields and N leaching were similar when mowing was based on banana nitrogen stress whatever the zone where cover crop residues were left (average yield = 9.8 and 13.7 kgDM ha^{-1} year^{-1}, and average N leaching = 81.6 and 137.0 kgN ha^{-1} year^{-1} for fertilization of 150 and 300 kgN ha^{-1} year^{-1}, respectively; Fig. 9). In contrast, when mowing was based on cover crop LAI, applying cover crop residues in intermediate area and small inter-row was more efficient than in the large inter-row or in the cover crop growth zone. For fertilization of 450 kgN ha^{-1} year^{-1} and the two ways of mowing, yields were higher when residues were left in small inter-row and intermediate area (19.3 kgDM ha^{-1} year^{-1} on average) whereas N leaching was 30 kgN ha^{-1} year^{-1} higher than when residues were left in large inter-row or in the zone of cover crop growth (Fig. 9). N losses by leaching tended to be higher when mowing was based on banana N stress than on cover crop LAI (from 2.3 to 24.8 kgN ha^{-1} year^{-1} on average); the highest differences were observed for the lowest level of fertilization (i.e., 150 kgN ha^{-1} year^{-1}).

In terms of management, the number of mowings (over the simulated period) was always higher when mowing was based on banana N stress rather than on cover crop LAI (data not shown). In both cases, the higher the amount of fertilization, the lower the frequency of mowings during the three banana crop cycles (every 5–10 weeks and 13–17 weeks on average for fertilization of 150–450 kgN ha^{-1} year^{-1}, when mowing was based on banana N stress and cover crop LAI, respectively). When mowing was based

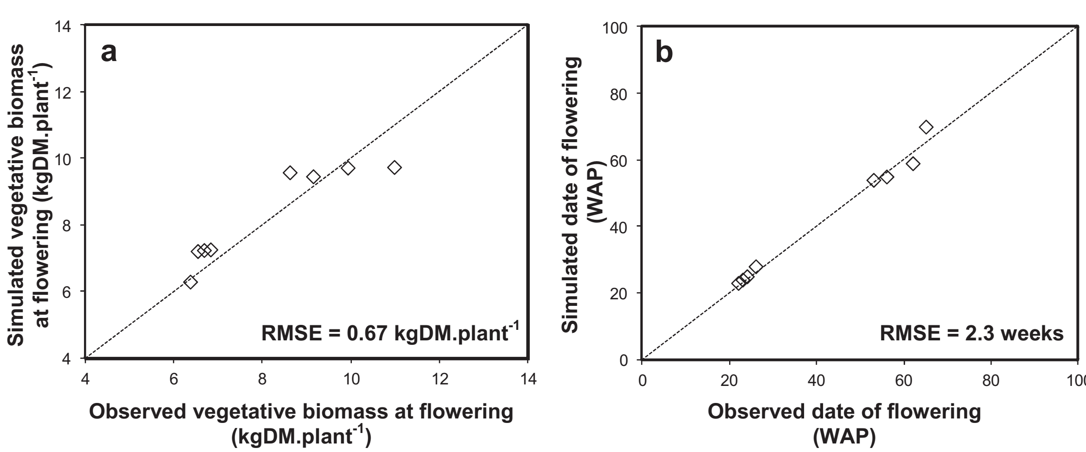

Fig. 5. Observed and simulated (a) vegetative biomass of banana crop at flowering (kgDM plant^{-1}) and (b) date of flowering in the fertilizer experiment. WAP = weeks after planting. The dotted line shows the 1:1 line.

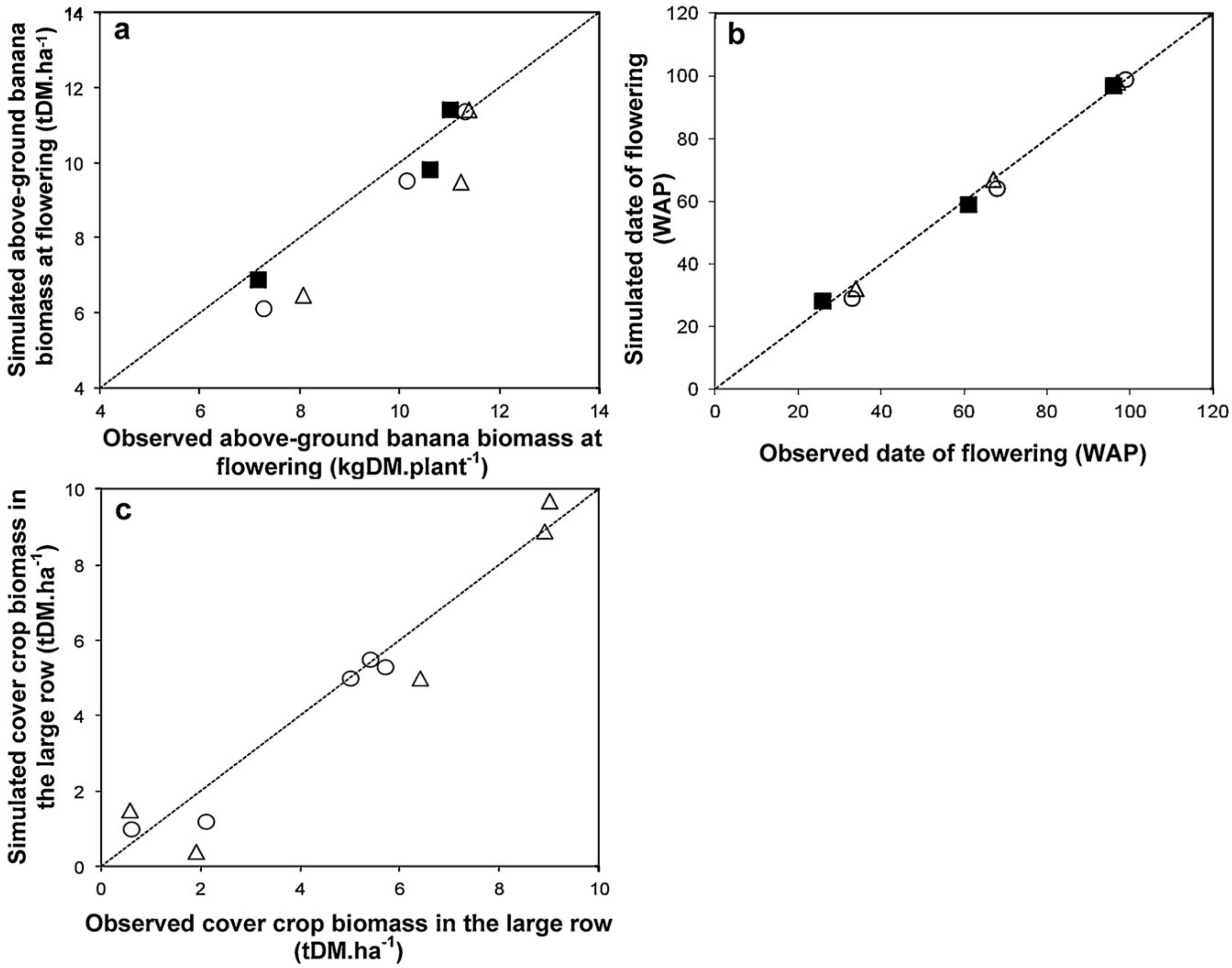

Fig. 6. Observed and simulated values of (a) dry matter of above-ground banana biomass at flowering (kgDM plant^{-1}), (b) date of flowering, and (c) cover crop biomass in large inter-row in cropping systems with *Brachiaria decumbens* (△) or *Cynodon dactylon* (○) as cover crop or on bare soil (■). The dotted line shows the 1:1 line. WAP = weeks after planting.

on cover crop LAI, the number of mowings varied between the different field zones. Mowing frequency was higher in the zone where residues were left after mowing, particularly when residues were left in the large inter-row (up to 9 mowings of difference) and similar in the other zones for all levels of fertilization. In the case residues were left in the zone where cover crop grew, the number of mowings was similar in all zones (around 15, 8, and 6 for a fertilization of 150, 300, and 400 kgN ha^{-1} year^{-1}, respectively).

4. Discussion

4.1. Model calibration and validation

The results of the "nstress" parameter calibration were close to those of Godefroy and Dormoy (1983, 40 kgN ha^{-1}). Differences in the crop cycle duration between the treatments (different levels of fertilization in calibration and presence of cover crops in the validation) were correctly simulated. The standard deviation calculated from experimental data was close to the error of the model (2.2 vs. 2.3 weeks). The highest difference observed in F0 (5 weeks late), could be due to an overestimation of the N stress applied to banana between the harvest of the first cropping cycle and the floral initiation during the second cropping cycle.

The validation procedure showed that despite the N stress overestimation, simulation results were consistent with field observations. The difference between simulations and observations in the CD treatment could be explained by an allelopathic effect of *Cynodon dactylon* on banana growth. This effect was not considered for experimentation as no study was available that considered this effect on banana. Nevertheless, allelopathy of *C. dactylon* was already observed in different situations; it can inhibit growth of other crops like pecan trees, cotton, or corn (Smith et al., 2001; Vasilakoglou et al., 2005). As this effect is not taken into account in the model, it may overestimate the biomass produced and the growth rate during the crop growth cycle. The allelopathic effect could also explain the early date of flowering in simulations and the difference of biomass at flowering (lower in the simulations). Nevertheless, despite the trend in underestimating the biomass at flowering, the difference between observed and predicted value remained low (<10% of the biomass on average, all treatments taken together). The partitioning of light and nitrogen resources in SIMBA-IC allowed us to simulate the overall functioning of the field as close as possible to the one observed in experiments. Comparison between observed and simulated mineral N stock in soil for fertilizer experiments showed that the model was able to reproduce the difference observed between treatments. Considering the functioning under banana row, the dynamics was well simulated despite a trend to overestimate the N stock during the second crop cycle (RMSE = 24 kgN ha^{-1}). Given the results of the simulations carried out to calibrate and evaluate the model, SIMBA-IC can be considered

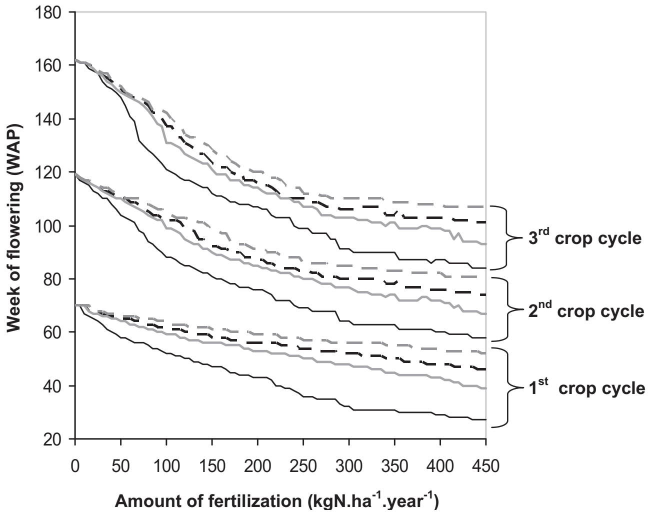

Fig. 7. Dynamics of the flowering date of banana related to fertilization amount (kgN ha^{-1} year^{-1}) and the zone of application (banana row: ▬▬, intermediate area: ▪ ▪ ▪ ▪, small inter-row: ▬▬, and large inter-row: ▪ ▪ ▪ ▪). WAP = weeks after planting.

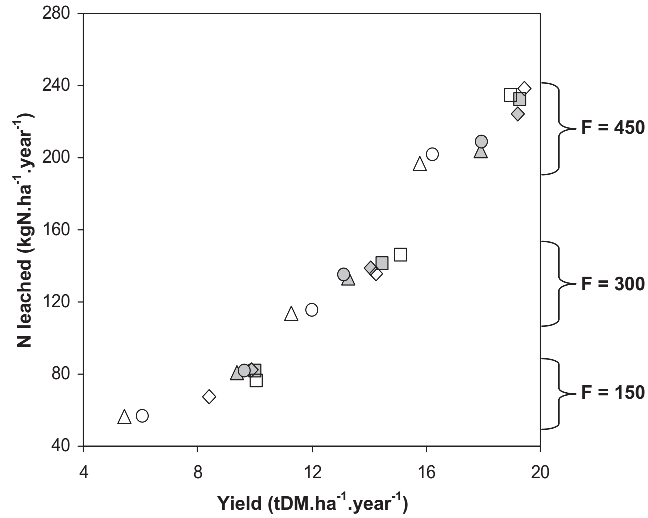

Fig. 9. Relationship between banana yield (tDM ha^{-1} year^{-1}) and N leached (kgN ha^{-1} year^{-1}) related to the N fertilization applied (F, in kgN ha^{-1} year^{-1}) and the zone where cover crop residues were left after mowing: intermediate area (◊), small inter-row (□), large inter-row (△), and growth zone (i.e., all zones except banana row, ○). Symbols are white when mowing relates to cover crop LAI (mowing if LAI ≥ 5), (b) and gray when mowing relates to banana nitrogen stress (mowing if stress < 0.5).

accurate and realistic enough to simulate banana cropping systems and to explore a range of cropping systems.

4.2. Resource partitioning

Nutrient and light partitioning in cover cropping systems are a main issue in realistically reproducing the interactions between the different crops in the system. In SIMBA-IC, light partitioning is semi-empirical; the influence of banana shading on suckers or on cover crops in the different field zones was based on the LAI. This allowed taking into account the dynamics of light partitioning between the mother banana, suckers, and cover crops. In the case of banana, vegetation strata are well differentiated and there is an asymmetric effect on light partitioning, i.e. banana crops are above cover crops. Thus, we did not have to take into account the possible shading of the cover crop on the cultivated crop, as in other cropping systems, e.g. wheat/maize or pea/barley (Corre-Hellou et al., 2009; Knorzer et al., 2011). This approach is in line with other modeling studies on intercropping systems based on tall, for example intercropped vineyards (Celette et al., 2010).

The zoning of the cover crop and N dynamics allowed representing spatialized management of the field. The N mineralization was adapted from Dorel et al. (2008) and Raphael et al. (2012), developed for banana cropping systems in the same climate and soil context. Nevertheless, determining the relationships between the different soil layers could improve our understanding of the interactions between banana and cover crop roots, as in the DSSAT model (Jones et al., 2003; Cabrera et al., 2007). Adding the N_2 fixation could also improve the model in cases of intercropping with legume plants. Corre-Hellou et al. (2009) added a relationship in the STICS intercrop model (Brisson et al., 2004) between N_2 fixation and crop growth rate to simulate pea/barley cropping systems. In our case, this modification requires new experimental data on legume cover crop, especially on the effect of the N available and the rate of atmospheric N fixation. Furthermore, it could be of interest to go further into the mechanisms of competition for resources between banana and cover crop. Such studies could include interaction at the level of roots systems.

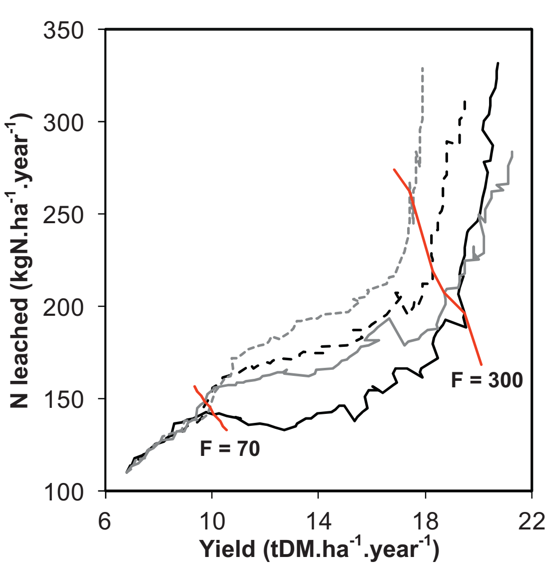

Fig. 8. Dynamics of banana yield (tDM ha^{-1} year^{-1}) and N leached (kgN ha^{-1} year^{-1}) related to the N fertilization applied (F, from 0 to 450 kgN ha^{-1} year^{-1}) and the zone of application (banana row: ▬▬, intermediate area: ▪ ▪ ▪ ▪, small inter-row: ▬▬, and large inter-row: ▪ ▪ ▪ ▪). The red lines indicate when fertilization was 70 and 300 kgN ha^{-1} year^{-1}.

4.3. Cropping system design

Managing plurispecific cropping systems is a major issue for research and farmers. Modeling is a powerful tool to explore a large range of cropping systems; in the case of banana intercropped systems, the model allowed exploring their layout to optimize nutrient resources and cover crop management. Several authors have used models to explore different management options considering fertilization, crop sowing date, or intercrop management (Nesme et al., 2006; Launay et al., 2009; Ripoche et al., 2011). Van der Laan et al. (2011) showed that for sugarcane, the Canegro-N model allowed optimal fertilization management to be determined based on inorganic N level or a delay of fertilization between crop growth cycles accounting for the remaining inorganic N. The results of the fertilization optimization based on amount and zone of application showed that a large leeway exists (between 100 and 300 kgN ha^{-1} year^{-1}) to propose banana cropping systems that satisfy environmental and agronomic performances. Simulations based on different levels of fertilization and two possible managements of cover crop growth (mowing activation based on cover crop LAI or banana nitrogen stress) suggest also that a management can be found to achieve satisfactory agronomic and environmental performances by applying cover crop residues in small inter-row or intermediate area even at low level of fertilization. The yields simulated at 300 kgN ha^{-1} year^{-1} are slightly higher than observed in Martinique (Agreste, 2011) where the level of fertilization currently used by farmers is close to this. The model, however, predicts that when mowing is based on banana N stress, farmers need to mow the cover crop very often, sometimes every five weeks. Such practices are not acceptable by farmers, especially because of their economic cost. In contrast, mowing based on cover crop LAI tended to let the cover crop compete strongly with banana. Nevertheless, this competition may be partially compensated by the application of residues in appropriate zones (small inter-row or intermediate area) or by a higher fertilization (e.g. 300 kgN ha^{-1} year^{-1}) as banana benefits from nitrogen resources and grows faster. Banana N stress and cover crop LAI were chosen as indicators for mowing, but they are not currently used by farmers. For N stress, such practices could be supported by the use of plant measures, such as SPAD chlorophyll meters. Further work has to be done to determine an easy-to-use indicator on field for cover crop management as cover crop height or a percentage of soil cover. These results imply that farmer's practices between these two cover crop management strategies should induce nitrogen stress for banana, and consequently an acceptance of a minimum yield loss. The model is currently being used in interaction with extension services to help design intercropping systems. Yet, more simulations are needed to explore flexibility in fertilization and cover crop management. A more adaptive management, i.e., flexible rules for fertilization and cover crop mowing according to the needs of banana crop over the crop cycle, could help limit N losses and competition for nutrients with cover crop. This type of work has been done for vineyard intercropping systems (Ripoche et al., 2011), in which a rule was created for users to choose between mowing or intercrop destruction according to grapevine water status. The water status was checked every two weeks to react rapidly and avoid compromising grapevine performances. Nevertheless, this could imply more constraints for farmers, as observed in our simulations when mowing was based on banana N stress. In future studies, this economic issue should be included as an evaluation criterion.

5. Conclusion

The SIMBA-IC model, with the representation of the different zones of a banana field, allows designing banana cover cropping systems taking into account differences in resource dynamics (light, nitrogen). The model validation showed that SIMBA-IC realistically simulates the impact of cover crop or fertilization on the performances of the cropping systems (agronomic: yield, environmental: leaching). Future research should focus on the relationships between the growth of crops and their management as well as on technical constraints related to the latter (labor, time required for cover crop management). Their implementation in the model could then help to assess the socio-economic performances of these cropping systems. Considering the design of innovative cropping systems, future works should consider the challenging issue of cropping systems based on a mixture of cover crop species.

Acknowledgments

This work was funded by the InterReg Project "Caribbean sustainable banana", and by the Project "Sustainable cropping systems design" from E.U. FEFER. We thank Gary Burkhart for the linguistic support.

References

Agreste, 2011. La banane, un pilier de l'agriculture des Antilles. Ministère de l'agriculture, de l'alimentation, de la pêche, de la ruralité et de l'aménagement du territoire http://www.agreste.agriculture.gouv.fr/IMG/pdf_primeur262.pdf. 4 p.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agriculture Ecosystems & Environment 74 (1–3), 19–31.

Bocquene, G., Franco, A., 2005. Pesticide contamination of the coastline of Martinique. Marine Pollution Bulletin 51 (5–7), 612–619.

Bonan, H., Prime, J.-L., 2001. Rapport sur la présence de pesticides dans les eaux de consommation humaine en Guadeloupe. Ministère de l'aménagement du territoire et de l'environnement, 77 pp.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.-P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. European Journal of Agronomy 18, 309–332.

Brisson, N., Bussière, F., Ozier-Lafontaine, H., Tournebize, R., Sinoquet, H., 2004. Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation. Agronomie 24 (6–7), 409–421.

Cabrera, V.E., Jagtap, S.S., Hildebrand, P.E., 2007. Strategies to limit (minimize) nitrogen leaching on dairy farms driven by seasonal climate forecasts. Agriculture Ecosystems & Environment 122 (4), 479–489.

Celette, F., Gaudin, R., Gary, C., 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. European Journal of Agronomy 28 (4), 153–162.

Celette, F., Ripoche, A., Gary, C., 2010. WaLIS—a simple model to simulate water partitioning in a crop association: the example of an intercropped vineyard. Agricultural Water Management 97 (11), 1749–1759.

Corre-Hellou, G., Faure, M., Launay, M., Brisson, N., Crozat, Y., 2009. Adaptation of the STICS intercrop model to simulate crop growth and N accumulation in pea-barley intercrops. Field Crops Research 113 (1), 72–81.

Derpsch, R., Sidiras, N., Roth, C.H., 1986. Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Paraná, Brazil. Soil & Tillage Research 8, 253–263.

Doltra, J., Munoz, P., 2010. Simulation of nitrogen leaching from a fertigated crop rotation in a Mediterranean climate using the EU-Rotate_N and Hydrus-2D models. Agricultural Water Management 97 (2), 277–285.

Dorel, M., Achard, R., Tixier, P., 2008. SIMBA-N: modeling nitrogen dynamics in banana populations in wet tropical climate. Application to fertilization management in the Caribbean. European Journal of Agronomy 29 (1), 38–45.

Ganry, J., 1980. Note de synthèse: le développement du bananier en relation avec les facteurs du milieu: action de la température et du rayonnement d'origine solaire sur la vitesse de croissance des feuilles. Etude du rythme de développement de la plante. Fruits 35, 727–744.

Godefroy, J., Dormoy, M., 1983. Dynamique des éléments minéraux fertilisants dans les sols des bananeraies martiniquaises. Fruits 38 (6), 451–459.

Jannoyer, M., 1995. Déterminisme du nombre d'organes reproducteurs d'une inflorescence de bananier (Musa acuminata, cv 'Grande Naine') INA-PG , Paris, 199 pp.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. European Journal of Agronomy 18, 235–265.

Knorzer, H., Grozinger, H., Graeff-Honninger, S., Hartung, K., Piepho, H.P., Claupein, W., 2011. Integrating a simple shading algorithm into CERES-wheat and CERES-maize with particular regard to a changing microclimate within a relay-intercropping system. Field Crops Research 121 (2), 274–285.

Launay, M., Brisson, N., Satger, S., Hauggaard-Nielsen, H., Corre-Hellou, G., Kasynova, E., Ruske, R., Jensen, E.S., Gooding, M.J., 2009. Exploring options for managing strategies for pea-barley intercropping using a modeling approach. European Journal of Agronomy 31 (2), 85–98.

Mazzoncini, M., Sapkota, T.B., Barberi, P., Antichi, D., Risaliti, R., 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil & Tillage Research 114 (2), 165–174.

Monteith, J.L., 1972. Solar radiation and productivity in tropical ecosystems. Journal of Applied Ecology 9 (3), 747–766.

Moonen, A.C., Barberi, P., 2008. Functional biodiversity: an agroecosystem approach. Agriculture Ecosystems & Environment 127 (1–2), 7–21.

Nesme, T., Brisson, N., Lescourret, F., Bellon, S., Crété, X., Plénet, D., Habib, R., 2006. Epistics: a dynamic model to generate nitrogen fertilisation and irrigation schedules in apple orchards, with special attention to qualitative evaluation of the model. Agricultural Systems 90 (1–3), 202–225.

Nyombi, K., van Asten, P.J.A., Leffelaar, P.A., Corbeels, M., Kaizzi, C.K., Giller, K.E., 2009. Allometric growth relationships of East Africa highland bananas (Musa AAA-EAHB) cv. Kisansa and Mbwazirume. Annals of Applied Biology 155 (3), 403–418.

Parton, W.J., Rasmussen, P.E., 1994. Long-term effects of crop management in wheat-fallow. 2. CENTURY model simulations. Soil Science Society of America Journal 58 (2), 530–536.
Ramos, M.E., Benitez, E., Garcia, P.A., Robles, A.B., 2010. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: effects on soil quality. Applied Soil Ecology 44 (1), 6–14.
Raphael, L., Sierra, J., Recous, S., Ozier-Lafontaine, H., Desfontaines, L., 2012. Soil turnover of crop residues from the banana (Musa AAA cv Petite-Naine) mother plant and simultaneous uptake by the daughter plant of released nitrogen. European Journal of Agronomy 38, 117–123.
Ripoche, A., Rellier, J.-P., Martin-Clouaire, R., Paré, N., Biarnès, A., Gary, C., 2011. Modelling adaptive management of intercropping in vineyards to satisfy agronomic and environmental performances under Mediterranean climate. Environmental Modelling & Software 26 (12), 1467–1480.
Singer, J.W., Malone, R.W., Jaynes, D.B., Ma, L., 2011. Cover crop effects on nitrogen load in tile drainage from Walnut Creek Iowa using root zone water quality (RZWQ) model. Agricultural Water Management 98 (10), 1622–1628.
Smith, M.W., Wolf, M.E., Cheary, B.S., Carroll, B.L., 2001. Allelopathy of bermudagrass, tall fescue, redroot pigweed, and cutleaf evening primrose on pecan. Hortscience 36 (6), 1047–1048.
Teasdale, J.R., 1996. Contribution of cover crops to weed management in sustainable agricultural systems. Journal of Production Agriculture 9 (4), 475–479.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418 (6898), 671–677.
Tixier, P., Malezieux, E., Dorel, M., Wery, J., 2008. SIMBA, a model for designing sustainable banana-based cropping systems. Agricultural Systems 97 (3), 139–150.
Tixier, P., Lavigne, C., Alvarez, S., Gauquier, A., Blanchard, M., Ripoche, A., Achard, R., 2011. Model evaluation of cover crops, application to eleven species for banana cropping systems. European Journal of Agronomy 34 (2), 53–61.
Van der Laan, M., Miles, N., Annandale, J.G., Du Preez, C.C., 2011. Identification of opportunities for improved nitrogen management in sugarcane cropping systems using the newly developed Canegro-N model. Nutrient Cycling in Agroecosystems 90 (3), 391–404.
Vasilakoglou, I., Dhima, K., Eleftherohorinos, I., 2005. Allelopathic potential of Bermudagrass and Johnsongrass and their interference with cotton and corn. Agronomy Journal 97 (1), 303–313.
Wery, J., Langeveld, J.W.A., 2010. Introduction to the EJA special issue on Cropping Systems Design: new methods for new challenges. European Journal of Agronomy 32 (1), 1–2.