

Modelling pest dynamics of new crop cultivars: The FB920 banana with the *Helicotylenchus multicinctus*–*Radopholus similis* nematode complex in Martinique

P. Tixier^{a,*}, F. Salmon^b, C. Chabrier^a, P. Quénéhervé^c

^a CIRAD, UPR 26, PRAM - BP 214 - 97285 Lamentin Cedex 2 - Martinique, French West Indies, France

^b CIRAD, UPR 75, PRAM - BP 214 - 97285 Lamentin Cedex 2 - Martinique, French West Indies, France

^c IRD, UMR RPB, PRAM - BP 214 - 97285 Lamentin Cedex 2 - Martinique, French West Indies, France

ARTICLE INFO

Article history:

Received 22 October 2007

Received in revised form 9 June 2008

Accepted 11 June 2008

Keywords:

Population model

Banana hybrids

Musa

SIMBA

Martinique

ABSTRACT

The synthetic banana hybrid FB920 (*Musa* spp., AAA group) has been designed to be resistant to Sigatoka and Black Leaf Streak Diseases, caused respectively by *Mycosphaerella musicola* and *Mycosphaerella fijiensis*. In addition to these features, the hybrids seem less susceptible to plant-parasitic nematodes, especially the burrowing nematodes (*Radopholus similis*) and the lesion nematode (*Pratylenchus coffeae*) than classic Cavendish cultivars, such as Williams, Grande Naine, or Poyo. This genetic modification drastically reduces pesticide use. Herein, we used the SIMBA model (a model to simulate phenology, growth, and plant-parasitic nematode/banana interactions) to examine the population dynamics of plant-parasitic nematodes in cropping systems with hybrid FB920 in various initial conditions. Results from field observations and simulations show that in the long-term, the spiral nematodes (*Helicotylenchus multicinctus*) can overtake the burrowing nematodes and that nematode populations are smaller than in Cavendish banana fields. This reduced capacity of FB920 to support multiplication of *R. similis* reduces the use of pesticides and thus re-creates favourable conditions for fauna, thereby increasing the global sustainability and resilience of banana agro-ecosystems.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

The early assessment of pest dynamics for a new cultivar (cv) is a major issue for plant-breeders and agronomists. Because of time and financial constraints, and the large number of hybrids to be tested, there are generally few measures on each cv and few studies on the long-term trends of the genotypes. Shorter et al. (1991) and Barbottin et al. (2006) proposed crop models to help breeders identify the best cvs for various practices, mostly on the basis of yield. Pest dynamics models initially developed to predict and manage pest populations can then be used to *ex-ante* evaluate new cvs in the long-term. The model should also be able to answer the main questions of the growers. So well-tested simulation approaches may offer a time- and cost-effective alternative to experiments for cv evaluation and management. Nevertheless, this evaluation step is rarely performed (Welch et al., 2002).

Plant-parasitic nematodes limit banana production for the export market, in which the Cavendish cv prevails (*Musa* spp., AAA group, cv. Cavendish). Export bananas cover nearly one million

hectare worldwide (FAOSTAT, 2007) and yield improvement in the absence of nematodes varies from 15 to 275% (Gowen and Quénéhervé, 1990). The burrowing nematode *Radopholus similis* (Rs) which generates extensive root lesions and results in toppling over of the plants, is considered the most detrimental pathogen of banana roots. The spiral nematode *Helicotylenchus multicinctus* (Hm) is widely distributed in all banana production areas; root lesions are much less damaging as they remain mostly superficial and thus disturb plant nutrition less and never cause toppling over (Quénéhervé, 2008).

Among banana cvs, tolerance against parasitic nematodes varies widely and the capacity to multiply species of nematodes varies from one cv to another (Quénéhervé et al., 2006). The variability of tolerance against plant-parasitic nematodes is partly explained by the level of condensed tannins in banana roots (Collingborn et al., 2000).

New synthetic hybrids are mostly designed for their properties of high yield and pest resistance. Here, we study the new synthetic banana hybrid FB920 (*Musa* spp., AAA group), which is resistant to *Mycosphaerella* leaf spot diseases of bananas caused by *Mycosphaerella musicola* (Sigatoka Disease) and *M. fijiensis* (Black Leaf Streak Disease). Such triploids are issued from conventional breeding techniques (Jenny et al., 2003), including diploid resistant genitors previously doubled with colchicine (Bakry et al., 2007).

* Corresponding author. Tel.: +596 (0) 596 42 30 17; fax: +596 (0) 596 42 30 01.
E-mail address: tixier@cirad.fr (P. Tixier).

Table 1
Name and description of variables and parameters of the SIMBA-POP and the SIMBA-NEM modules

Inputs variables	Meaning
<i>SIMBA-POP module</i>	
T_t	Weekly temperature (°C)
<i>SIMBA-NEM module</i>	
RB_t	Fresh root biomass at step t (kg)
Output variables	
<i>SIMBA-POP module</i>	
F_t	Number of flowering plants at step t
H_t	Number of harvested plants at step t
<i>SIMBA-NEM module</i>	
NRS_t	Rs density in banana roots
NHm_t	Hm density in banana roots
Parameters	
<i>SIMBA-POP module</i>	
ST_s	Sucker selection threshold (°C)
$a_s; b_s; c_s$	Sucker selection log-normal curve parameters
ST_f	Flowering threshold (°C)
$a_f; b_f; c_f$	Flowering log-normal curve parameters
<i>SIMBA-NEM module</i>	
$C_{Rs}Pot$	Population growth rate of Rs
$C_{Hm}Pot$	Population growth rate of Hm
K_{Nem}	Total nematode carrying capacity

Where t is the step of the model; Rs for *Radopholus similis* and Hm for *Helicotylenchus multicinctus*.

In the present work, we present a model-based method to predict the long-term trends of the FB920-Rs-Hm complex and we propose explanations for trends highlighted by simulations.

2. Material and methods

2.1. Model description

We used the SIMBA framework to conduct our simulations. The SIMBA model was developed in the Stella platform (High Performance System[®]; Lebanon, NH). It includes modules that account for the major processes of the simulated field (Tixier et al., 2004b). It simulates, at the week time-step, the effects of crop rotations and agro-management on soil, water, nematode, yield, and economic outputs (Tixier et al., 2008). We used the two modules SIMBA-POP and SIMBA-NEM (Tixier et al., 2004a; Tixier et al., 2006) to simulate the phenology of the crop, its associated root biomass dynamics, and the plant-parasitic nematode dynamics. Table 1 presents the

SIMBA-POP and SIMBA-NEM variables and parameters used for the simulations.

2.1.1. Banana phenology and root biomass dynamics

Bananas are rhizomatous herbaceous plants whose terminal bud produces the inflorescence. Each mat successively produces a series of stems from a lateral shoot, and each stem produces a single bunch. The sequence can be repeated for 1 to 50 generations or more, which means that the mat can be considered perennial. The main developmental stages of banana plants include sucker appearance (which the farmer may influence by selecting the sucker early or late), growth, flowering, and harvest. Banana crops are a collection of individual plants derived from vegetative propagules. They develop at their own rhythm and do not follow a synchronous cycle. When the stages of new sucker, flowering, and harvest occur, the population structure spreads following log-normal functions (Tixier et al., 2004a). Hence, at any given time, a banana crop consists of a population of individual plants at various developmental stages. The dynamics of banana bunch harvest follow peaks whose amplitudes tend to be wider over time, up to a continuous harvest after five to seven cropping cycles. The development of bananas and the dynamics of the harvest depend on the climate, in particular the temperature (at least in the case of appropriated water and mineral supply). The FB920 banana hybrid was assumed to follow the same phenology as the Cavendish cv but with different parameters.

The SIMBA-POP module (Tixier et al., 2004a) was used to simulate the population dynamics of banana fields with a weekly step t . The only input data is the mean weekly temperature. Outputs include the number of flowering and harvested plants for each week of the simulation. This module is driven by the heat unit accumulated and stochastic laws (flowering, sucker selection, and harvest dispersions). A growth module linked to SIMBA-POP was used to calculate the biomass of roots for the whole banana field. This module includes simulation of leaf area index, vegetative biomass (leaves, pseudo-stem, and roots), and yield (number and weight of fruit per bunch).

2.1.2. Plant-parasitic nematode dynamics

The SIMBA-NEM module (Tixier et al., 2006) was used to simulate the population dynamics of Rs and Hm in the FB920 systems. SIMBA-NEM is based on a cohort chain structure and a logistic function to describe population growth in relation to (i) an environmental carrying capacity (K_{Nem}) depending on the available banana root biomass, (ii) an intrinsic growth rate (C_{Rs} for Rs, C_{Hm} for Hm), and (iii) the interspecific competition. This module accounts for different initial situations of nematode populations, such as after fallow (Chabrier and Quénehervé, 2003) or after sugarcane (Berry et al., 2007).

Table 2
Location, altitude, soil type, previous crop, planting date of the six fields planted with the FB920 banana cultivar and the nematode population measures

Fields name	Plot location	Altitude (m)	Soil type	Previous crop	Planting date	Number of measures	Uses
CRES	14°48'16.0"N 61°01'58.5"W	125	Halloysite soil	Banana	09/09/04	10	Calibration
DURA	14°48'50.6"N 61°01'56.2"W	130	Halloysite soil	Citrus	25/07/04	6	Calibration
GALI	14°43'00.1"N 60°57'25.6"W	7	Alluvial soil	Fallow	25/08/04	8	Calibration
MALG	14°42'32.6"N 60°58'20.7"W	75	Ferrisoil	Sugarcane	27/08/04	8	Calibration
CHAR	14°48'12.9"N 61°02'04.9"W	170	Halloysite soil	Banana	04/08/04	14	Validation
PIRO	14°47'36.0"N 61°03'25.4"W	150	Andisol	Banana	06/08/04	24	Validation

Table 3

Calibration of SIMBA-POP parameters for FB920 using fields CRES, DURA, GALI, and MALG

Parameter	Mean value	Standard deviation
ST_s	1375	260
a_s	1.00	–
b_s	3.06	0.86
c_s	0.32	0.09
ST_f	1937	143
a_f	1.00	–
b_f	4.78	1.26
c_f	0.54	0.15

2.2. FB920 data

Between May 2005 and April 2007, we measured the banana phenology (interval between planting, flowering, harvest; distribution of flowering over time), banana growth (yield, plant biomass), and the nematode population dynamics in six banana fields in Martinique, 1 ha each, planted with the banana hybrid FB920 at the density of 1500 plants per hectare (Table 2). The planting material was issued from *in vitro* culture. The number of flowering and harvesting plants was measured every week during the experiment. The mean temperature of every field was measured using Tinytag® sensors (Gemini data loggers™). For each field, a composite sample was constituted with 5 primary roots of 20 banana plants. Then, the enumeration of each species of plant-parasitic nematodes was carried out after extraction by the centrifugation–flotation method (Coolen and D’Herde, 1972). Nematode populations were expressed as the number of nematodes per gram of fresh root biomass. Four fields were used for the calibration of the model and two were used for the validation (CHAR and PIRO plots).

2.3. Calibration of SIMBA for the FB920

2.3.1. Calibration of the phenology and root biomass dynamics

Table 3 presents the calibration of the SIMBA-POP module for the FB920 phenology. We performed parameter fitting for the four fields used for calibration (CRES, DURA, GALI, MALG). The mean value of each parameter (ST_s ; a_s ; b_s ; c_s ; ST_f ; a_f ; b_f ; c_f ; ST_h) was considered to be the calibrated value.

2.3.2. Calibration of the plant-parasitic nematode dynamics

Parameters C_{Rs} , C_{Hm} , and K_{NemPot} were fitted to minimize the error between measures and simulations for the four fields used for calibration (CRES, DURA, GALI, MALG). For each dataset, the initial number of each species of nematodes was used as the first data of the dataset. The parameters and initial data for SIMBA-NEM are in Table 4. Parameters C_{Rs} , C_{Hm} , and $nemPot$ K_{NemPot} had a large standard deviation, as did the measured nematode densities: up to 30%. This variability, however, is compatible with the overall goal of the model, i.e. to give an order of magnitude for nematode infestation over time and to give the long-term trends.

Table 4

Calibration of SIMBA-NEM parameters for FB920 using fields CRES, DURA, GALI, and MALG

Parameter	Mean value	Standard deviation
C_{RsPot}	0.602	0.105
C_{HmPot}	0.796	0.214
K_{Nem}	51.4	19.3

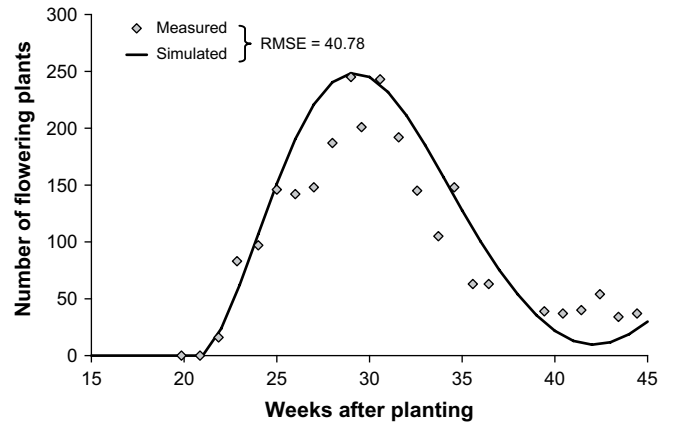


Fig. 1. Number of flowering bananas measured and simulated with SIMBA-POP model per week for the FB920 cultivar in field PIRO.

3. Simulation results

3.1. Validation of the FB920 phenology

Fig. 1 presents the measured and simulated number of flowering plants for fields PIRO. The root mean square error (RMSE) is 40.78, and r^2 is 0.87. This predictive accuracy allows one to simulate the development of the FB920 banana population over time with respect to the specificities of this cv; i.e. its short cropping cycle length between 20 and 40 weeks for the first cropping cycle relative to 35–55 weeks for the Cavendish cvs in similar climate conditions.

Fig. 2 presents the simulation of the flowering dynamics of FB920 and its associated root biomass dynamics. Flushes of root biomass correspond to the growth of banana suckers that emit roots from their early growth period to flowering. Root dynamics are characterized by successive flushes in relation with shoot phenology. New roots are emitted up to the flowering stage of the mother plant. Sucker roots are present and develop at the same time as those of the mother plant.

3.2. Validation of the plant-parasitic nematode dynamics

Fig. 3 presents the simulations of the nematode population dynamics (R_s and H_m) for CHAR and PIRO fields, using the calibration of the four others fields. For these two situations, RMSE values are 13.18 and 5.17 for R_s and 8.88 and 10.60 for H_m , for CHAR and PIRO respectively. The overall RMSE are 11.24 and 8.34 for CHAR and PIRO respectively, corresponding to 36.2% and 19.4% of the maximum observed values. Even though it is low, this precision

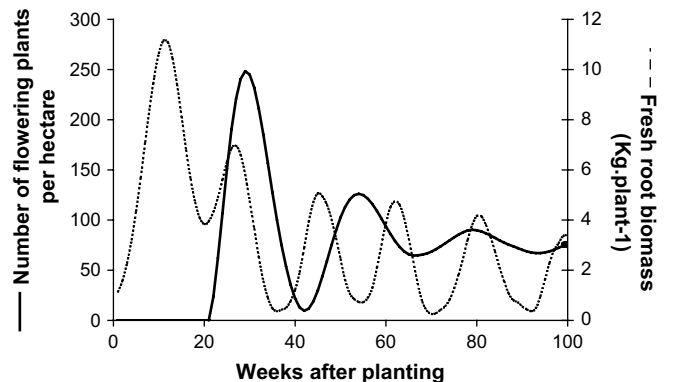


Fig. 2. Number of flowering bananas and fresh root biomass (in kg per plant) for a 100-week simulation, using parameters of FB920 cultivar and inputs corresponding to field PIRO.

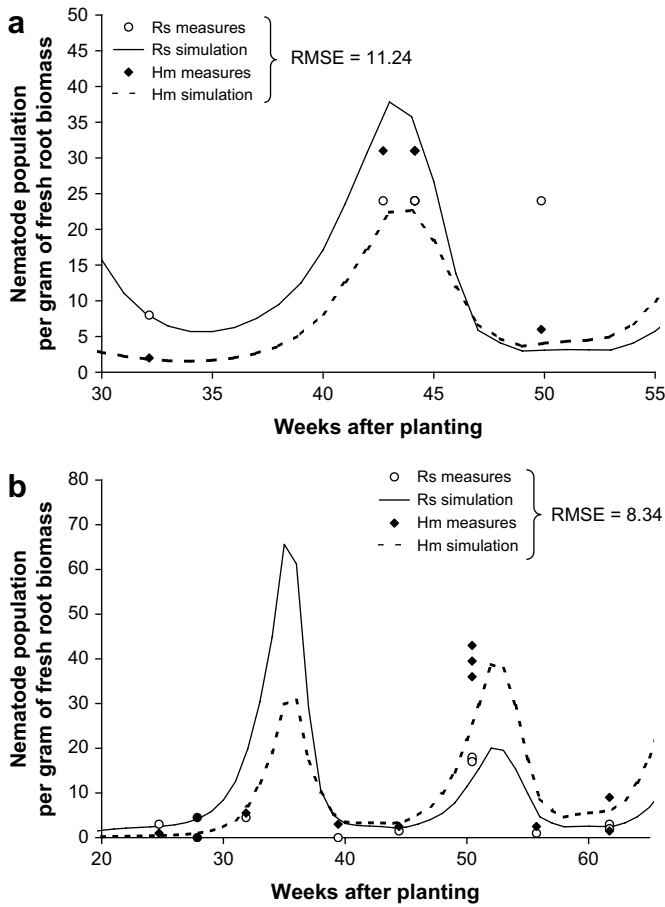


Fig. 3. Measured and simulated Rs and Hm populations for field CHAR (Fig. 3a) and for field PIRO (Fig. 3b).

is sufficient to help in nematode management because it allows one to determine the periods of low population, exponential growth, or high population. The overall population dynamics are well simulated by the model, and the peaks of population of Rs and Hm are correctly simulated, as shown for weeks 43 and 44 (Fig. 3a) and week 51 (Fig. 3b).

3.3. Long-term prospecting/exploration with the model

We used the SIMBA model to explore the long-term nematode population dynamics in FB920 systems with different initial populations of nematodes (+++, ++, and + are 0.1, 0.001, and 0.00001 nematodes per gram of fresh root respectively). Fig. 4 highlights the fact that Hm overtakes Rs in all initial conditions. The co-existence of both simulated species in the long-term, without complete exclusion of one species, is in line with our long-term observations on other cvs of banana. However, in the case of FB920 banana system, the burrowing nematodes Rs do not overtake all other species as in usual Cavendish systems.

4. Discussion

Results and simulations show that in the long-term, Hm populations can overtake Rs populations and that global nematode populations are lowered compared to Cavendish bananas such as Williams, Grande Naine, or Poyo. K_{Nem} was calibrated at 51.4 (nematodes per gram of fresh root), which is only about 10% of the value for Cavendish cvs (Tixier et al., 2006). This indicates that the capacity of the roots of FB920 to multiply these nematodes is much

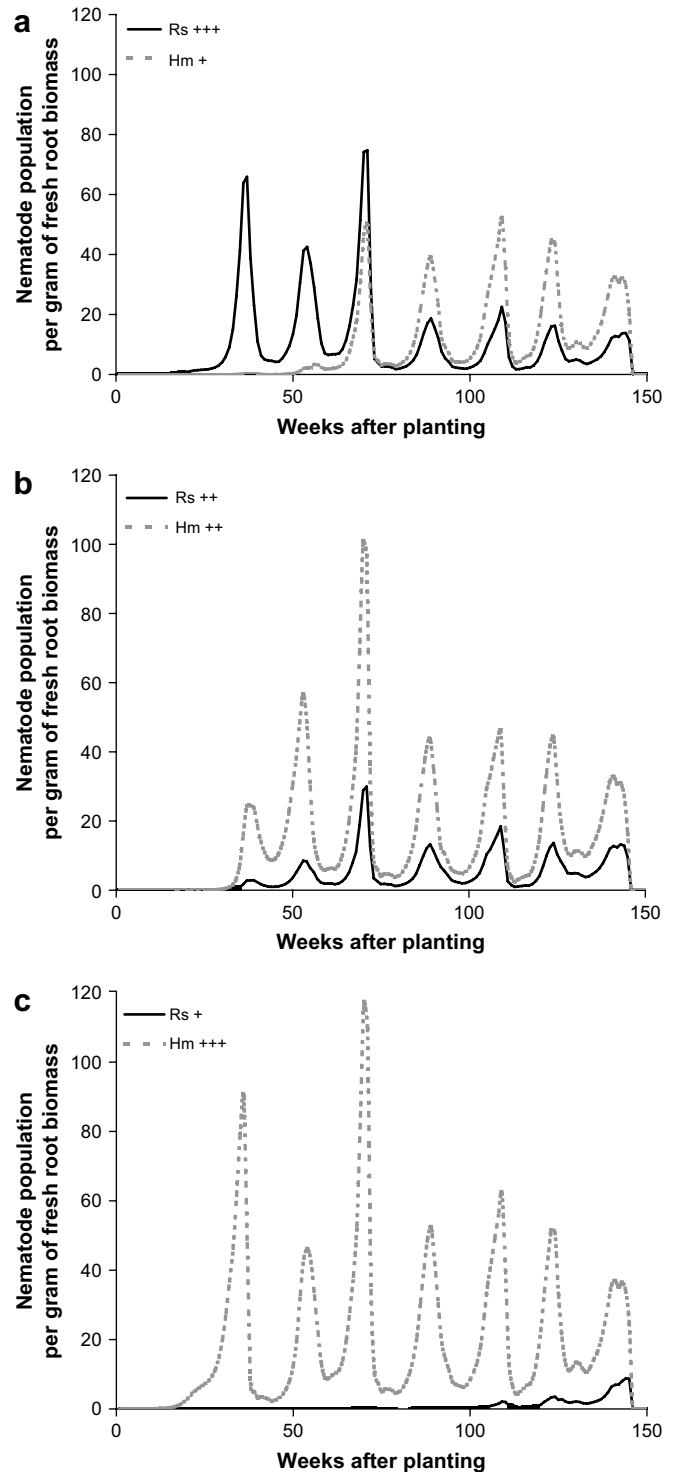


Fig. 4. Exploration with the SIMBA-NEM model of the long-term Rs and Hm populations for the FB920 banana; with different initial populations (+++, ++, and + are 0.1, 0.001, and 0.00001 nematodes per gram of root respectively for the initial inoculums). Inoculums are +++ and + for Rs and Hm in Fig. 4a, ++ and ++ in Fig. 4b, and + and +++ in Fig. 4c.

lower than for Cavendish banana cvs. C_{RsPot} and C_{HmPot} were calibrated at values similar to the one of Cavendish; i.e. C_{RsPot} was 0.957 in Tixier et al. (2006). This shows that nematode populations in FB920 systems tend to grow as fast as in other cvs but that they reach a lower level when they equilibrate at mid-term. In the long-term, the ratio between the two simulated species is proportional to the ratio between the two intrinsic growth rates. This correlation

can be explained by the fact that C_{RsPot} and C_{HmPot} partly represent the affinity of Rs and Hm for the FB920 cv. Our study is valid only for the Rs–Hm–FB920 complex; other trends are observed for other cvs of banana (Mateille, 1992). The hypothesis of ‘succession in the competitive hierarchy of nematodes’ (Quénéhervé, 1990) gives another highlight of the interaction between Rs and Hm. Indeed, Rs is known as the first nematode species (primary invader) to exploit newly emerging banana roots, while Hm do it secondarily. Therefore, for a given cv when Rs develops less, there are more root resources available for Hm.

Because Hm is less damaging for the root system, with no disrupting roots, and because FB920 has a lower capacity to allow the burrowing nematode Rs to multiply, systems based on this synthetic hybrid may further reduce the massive use of pesticides and thus re-create favourable conditions for fauna of the agro-ecosystem, thereby increasing the global sustainability and resilience of such banana cropping systems. Nevertheless, in other mostly subtropical locations or in absence of Rs, Hm is considered as damaging as Rs, e.g. in Israel (Minz et al., 1960), South Africa (Jones, 1979), and Florida (McSorley & Parrado, 1986). This difference in damage might be explained by different soil types and different cropping contexts (Gowen et al., 2005).

It is not yet clear if and how the population dynamics of nematodes (Quénéhervé, 1988) may change the trends observed and simulated for Rs and Hm in the case of FB920 systems. Similar cases were reported for Rs and *Pratylenchus coffeae* (Fallas et al., 1996). However, in the case we studied, the soil-climate conditions were contrasted and the Hm preponderance was observed in all conditions. Furthermore, the conditions of Martinique can be considered representative of a wide range of areas of banana production worldwide. The current model can be adapted to account for the effect of soil moisture and temperature etc.

Further field experiment studies should include more than two species of nematodes, especially *P. coffeae* and *Meloidogyne* spp. These are also very important (Gowen et al., 2005) in assessing FB920 in wider contexts of plant-parasitic nematode complexes, e.g. West Africa or Latin America. Nevertheless, one limit of our study is that it does not account for the effect of nematodes on the growth of banana. This should be the next step of our modelling approach and will call for more detailed research on the species by species effect on banana physiology.

This study illustrates the need for more in-depth studies on the dynamics of plant-parasitic nematodes of new cvs of banana. Indeed, further studies should measure the nematode populations more frequently. Furthermore, it would be of interest to carry out some measurements with a high initial population of plant-parasitic nematodes, thus allowing early and precise calibration of the nematode-banana model.

5. Conclusion

The modelling approach was used to find trends in plant-parasitic nematode populations by using early measures of populations for a new cultivated cv of banana. Pest population models that account for the diversity of the crop may be useful tools for agronomists and plant-breeders. The general trends in pest dynamics revealed by the model simulation should help agronomists optimize the conditions in which these new cvs will be grown. Thus in the future, plant-parasitic nematode populations should be measured early to ensure fast calibration of the model. In the specific case of FB920, the model shows favourable trends, but in other cases models should be helpful to detect, as early as

possible, cvs with major drawbacks with regard to nematode parasitism.

Acknowledgements

We thank farmers of Martinique for their help in the constitution of the phenological and nematode database. We also thank Eric Chiffirin and Olivier Birba (CIRAD) for data collection.

References

- Bakry, F., Paulo de la Reberdière, N., Pichot, S., Jenny, C., 2007. In liquid medium colchicine treatment induces non chimerical doubled-diploids in a wide range of mono- and interspecific diploid banana clones. *Fruits* 62, 3–12.
- Barbottin, A., Le Bail, M., Jeuffroy, M.H., 2006. The azodyn crop model as a decision support tool for choosing cultivars. *Agron. Sustain. Dev.* 26, 107–115. doi:10.1051/agro:2006003.
- Berry, S., Spaull, V.W., Cadet, P., 2007. Impact of harvesting practices on nematode communities and yield of sugarcane. *Crop Prot.* 8, 1239–1250. doi:10.1016/j.cropro.2006.10.022.
- Chabrier, C., Quénéhervé, P., 2003. Control of the burrowing nematode (*Radopholus similis* Cobb) on banana: impact of the banana field destruction method on the efficiency of the following fallow. *Crop Prot.* 22, 121–127.
- Coolen, W.A., D’Herde, C.J., 1972. A Method for the quantitative extraction of nematodes from plant tissue. Ministry of Agriculture of Belgium, Agricultural Research Administration, Belgium, 77 p.
- Collingborn, F., Gowen, S., Mueller-Harvey, I., 2000. Investigation into the biochemical basis for nematode resistance in roots of three *Musa* cultivars in response to *Radopholus similis* infection. *J. Agric. Food Chem.* 48, 5297–5301.
- Fallas, G.A., Hahn, M.L., Fargette, M., Burrows, P.R., Sarah, J.L., 1996. Molecular and biochemical diversity among isolates of *Radopholus* spp. from different areas of the world. *J. Nematol.* 28, 422–430.
- FAOSTAT, 2007. Food and agriculture organization, statistical databases. Available from: <<http://faostat.fao.org/>>.
- Gowen, S., Quénéhervé, P., 1990. Nematode parasites of bananas, plantains and abaca. In: Luc, M., Sikora, R.A., Bridge, J. (Eds.), *Plant Parasitic Nematodes in Subtropical and Tropical Agriculture*. CAB International, Wallingford, UK, pp. 431–460.
- Gowen, S., Quénéhervé, P., Fogain, R., 2005. Nematode parasites of bananas and plantains. In: Luc, M., Sikora, R.A., Bridge, J. (Eds.), *Plant Parasitic Nematodes in Subtropical and Tropical Agriculture*, second ed. CAB International, Wallingford, UK, pp. 611–643.
- Jenny, C., Tomekpe, K., Bakry, F., Escalant, J.V., 2003. Conventional breeding of bananas. In: *Proceedings of Mycosphaerella leaf spot diseases of bananas International Workshop*, San José, Costa-Rica, 20–23 May, 199–208.
- Jones, R.K., 1979. Control of *Helicotylenchus multicinctus* parasitizing bananas using systemic nematicides. *Nematropica* 9, 147–150.
- Mateille, T., 1992. Comparative development of three banana-parasitic nematodes on *Musa acuminata* (AAA group) cvs Poyo and Gros-Michel vitro-plants. *Nematologica* 38, 203–214.
- McSorley, R., Parrado, J.L., 1986. *Helicotylenchus multicinctus* on bananas: an international problem. *Nematropica* 16, 73–91.
- Minz, G., Ziv, D., Strich-Harari, D., 1960. Decline of banana plantations caused by spiral nematodes in the Jordan valley and its control by DBCP. *Ktavim* 10, 147–157.
- Quénéhervé, P., 1988. Population of nematodes in soils under banana, cv. Poyo, in the Ivory Coast. 2. Influence of soil texture, pH and organic matter in nematode populations. *Rev. Nématol* 11, 245–251.
- Quénéhervé, P., 1990. Spatial arrangement of nematodes around the banana plant in the Ivory Coast: related comments on the interaction among concomitant phytophagous nematodes. *Acta Oecol* 6, 875–886.
- Quénéhervé, P., Marie-Luce, S., Barout, B., Grosdemange, F., 2006. Une technique de criblage variétal précoce des bananiers envers les nématodes phytoparasites. *Nematology* 8, 147–152.
- Quénéhervé, P., 2008. Integrated management of banana nematodes. In: Ciancio, A., Mukerji, K.G. (Eds.), *Integrated Management of Fruit Crops Nematodes*. Springer, The Netherlands, pp. 1–54.
- Shorter, R., Lawn, R.J., Hammer, G.L., 1991. Improving genotypic adaptation in crops – a role for breeders, physiologists and modellers. *Exp. Agric.* 27, 155–175.
- Tixier, P., Malézieux, E., Dorel, M., 2004a. SIMBA-POP: a cohort population model for long-term simulation of banana crop harvest. *Ecol. Model* 180, 407–417. doi:10.1016/j.ecolmodel.2004.04.028.
- Tixier, P., Malézieux, E., Dorel, M., Wery, J., 2004b. SIMBA: a comprehensive model for agro-ecological assessment and prototyping of banana based cropping systems. An application to the banana cropping systems in French West Indies. In: *The 4th International Crop Science Congress*, Brisbane, September 2004.
- Tixier, P., Risède, J.M., Dorel, M., Malezieux, E., 2006. Modelling population dynamics of banana plant-parasitic nematodes: a contribution to the design of sustainable cropping systems. *Ecol. Model* 198, 321–331. doi:10.1016/j.ecolmodel.2006.05.003.
- Tixier, P., Malézieux, E., Dorel, M., Wery, J., 2008. SIMBA: a comprehensive model for evaluation and prototyping of banana-based cropping systems. *Agric. Syst.* 97, 139–150. doi:10.1016/j.agry.2008.02.003.
- Welch, S.M., Jones, J.W., Brennan, M.W., Reeder, G., Jacobson, B.M., 2002. PC-Yield: model-based decision support for soybean production. *Agric. Syst.* 74, 79–98.